FOREST RESOURCES COMMISSION

Background Papers - Volume 8

Timber Harvesting
- J. P. (Hamish) Kimmins

91-04586/

FOREST RESOURCES COMMISSION

Background Papers - Volume 8

Timber Harvesting
- J. P. (Hamish) Kimmins

The views expressed in independent reports prepared for the Forest Resources Commission are those of the authors and not necessarily those of the Commission. They are published in their entirety for the use and interest of the public as background studies to the April 1991 Report of the Commission to the Minister of Forests.

TIMBER HARVESTING

A DISCUSSION PAPER FOR THE

B.C. FOREST RESOURCES COMMISSION

BY

J.P. (HAMISH) KIMMINS

PROFESSOR OF FOREST ECOLOGY

DEPARTMENT OF FOREST SCIENCES

FACULTY OF FORESTRY

UNIVERSITY OF BRITISH COLUMBIA

VANCOUVER, B.C.

MAY 10th, 1990

EXECUTIVE SUMMARY

1. The current public concern about forest practices in British Columbia is predictable. Considering the world-wide growth in awareness of the importance of the environment, and the historical patterns of development of forestry in democratic countries, it would have been surprising had it not occurred. Forestry has generally progressed from an early centralized phase, employing policies and regulations that were administratively-based rather than biologically-based, to a more ecologically sensitive, decentralized phase. It has evolved from a preoccupation with providing strategic and commercial raw materials, to an increasing focus on the local concerns and needs of society, and a greater recognition of non-timber values and the need for management based on sound scientific principles. Forestry in different parts of the world is currently in various different stages of this progression. In British Columbia we have only recently emerged from the centralized administrative phase into the ecologically-based phase. Considering the trends in public opinion in the province, it is time to accelerate the transition to the most mature phase of forest resource management: socially and ecologically-based forestry.

2. Evaluation of the impacts of timber harvesting cannot be successful unless it is based on an understanding of the overall objectives and techniques of forest management, and the role of harvesting in silviculture (the growing of tree crops). Similarly, those charged with undertaking the evaluation must be familiar with the basic principles of forest ecosystem ecology, and with the concepts of ecological change, ecosystem resilience, and the determinants of the recovery of ecosystems from disturbance.

3. Historically, the choice of harvesting system in British Columbia was determined largely by engineering and economic considerations, rather than by any consideration of the long-term effects of the harvest on tree productivity and other resource values. This past preoccupation with engineering and economics is understandable. It reflects: 1) the engineering problems associated with harvesting large, old trees in steep mountainous country; 2) the high costs of road construction in many parts of British Columbia; 3) the frequently long haulage distance to mills or markets; 4) the traditional separation between the professional foresters who were responsible for reforestation and the growing of the next crop, and the engineers who were responsible for accessing the forests, building roads and bridges, and conducting the "engineering job" of harvesting old growth forest; 5) the past lack of legal requirements in forest management licence or tenure contracts that would ensure the protection of soil and long-term site productivity; and 6) a lack of adequate understanding of the principles of forest management by many of the foresters in British Columbia, many of whom also have an inadequate understanding of, and sensitivity to, forest soil and the

determinants of rotation length productivity. These deficiencies in the technical knowledge of some of B.C.'s professional foresters are presumably a consequence, in part, of the content of the curriculum in their undergraduate education.

4. More recently, the selection of the harvesting system to be used on a particular site has been determined by a much wider variety of factors. In many cases, there has been little choice as to which system would be used because of environmental, economic, silvicultural, or technical constraints. However, the selection has sometimes reflected a lack of clearly stated stand and forest management objectives, and of adequate planning and control of the harvest phase of silviculture. For example, an aerial or cable system should be chosen where there are problems of slope instability, soil sensitivity to compaction, or the need for extensive roads if a ground-based harvesting system were to be used. Yet, skidders (large, powerful, rubber-tired tractors) have sometimes been used when a cable system would have been preferable, simply because they were relatively inexpensive to operate, or because no other equipment was available. Although practical considerations will always be important, it is time for issues of sustainability, long-term site productivity, and non-timber resource values to play a much greater role in the choice of harvesting system and how the chosen system is implemented. The recently implemented Pre-harvest Silvicultural Prescription provides a mechanism by which silvicultural, ecological, wildlife and other non-timber values can be considered alongside economic, engineering and other technical factors in the selection of a harvesting system for a particular site.

5. The impacts of harvesting on the forest can be considered in terms of impacts on individual ecosystems and impacts on the whole forest. Local ecosystem impacts should be evaluated in terms of soil impacts, alterations to the forest microclimate, and impacts on the biota (plants, animals and microbes):

a) Timber harvesting can have negative effects on soil organic matter and nutrient inventories, although it may have positive effects on nutrient availability in the short run. If the rotation is too short, or the utilization of the biomass too intensive, site fertility and tree growth can be reduced significantly. Some types of harvesting systems can adversely affect soil structure (the "architecture" of the soil), aeration, and hydrology. Such negative impacts will reduce tree growth and site productivity, and will increase the risk of erosion and landslides ("mass wasting"). Loss of organic matter and soil structure can negatively affect the soil organisms which are vital for the maintenance of soil fertility.

Harvesting can result in periods of slope instability five to twenty years after logging as the roots of the cut trees decay and their contribution to soil strength is reduced. However, most

cases of slope instability are associated with roads. Instability caused by root deterioration is a greater problem with clearcutting than with uneven-aged harvesting systems, but because the latter may involve a much greater length of roads, especially on steep slopes, uneven-aged harvesting systems will not necessarily pose less problems than clearcutting, which would normally employ an aerial cable system in such topography. Alterations of slope hydrology can also have serious consequences for slope stability and can cause subsequent slope failure; most major alterations in slope hydrology are caused by roads.

In many cases, there are few if any negative impacts of harvesting on soils, but in some cases significant soil and site damage has been done. Sometimes recovery from this damage requires only a few years: in others it may take centuries. In many cases, most of the damage done to the soil and the site is associated with roads. Permanent roads in steep mountain areas can contribute to slope instability if not located, constructed and maintained correctly, and temporary roads or skid trails have often resulted in soil compaction, displacement and erosion.

b) Timber harvesting can have either positive or negative effects on soil and site microclimates. Microclimatic changes caused by clearcutting can warm cold northern forest soils, but can raise the surface soil temperature in hot, dry, southern forests so high that tree seedlings cannot survive. Clearcutting can benefit light-demanding trees and understory plants, but can damage the shade foliage of shade-tolerant advance regeneration. It can also create radiation frost problems if not accompanied by appropriate site preparation techniques. Microclimatic changes caused by harvesting are less persistent than soil changes. The forest microclimate recovers as soon as the forest regrows. Microclimatic changes are much less with uneven-aged harvesting systems than with clearcutting.

c) The effect of timber harvesting on the plant community depends on the extent of the removal of above-ground live plant biomass, the presence of roots and stumps that can resprout, of ungerminated seeds and spores in the soil, and of adjacent sources of seeds and spores that can contribute to the revegetation of denuded areas. Harvesting generally has a less dramatic effect on the composition of the plant community than subsequent site treatments such as slashburning or mechanical site preparation, although the increased light levels and altered microclimate caused by the removal of the forest canopy certainly plays a major role in determining the plant species composition following harvesting. Uneven-aged harvesting systems normally result in less change to the plant community than clearcutting. The duration of harvest-induced effects on the vegetation depends on the speed of revegetation and the rate at which the process of succession (the process of ecosystem recovery from disturbance) re-establishes the original vegetation conditions.

d) The effects of timber harvesting on animals is largely a function of the alteration of their habitat, which for most animals reflects the change in the plant community. Some animal species are increased in abundance by harvesting, some are decreased, and others remain unchanged. They simply adapt to the new conditions. Generally, the synchronous clearcut harvesting of very large areas (entire large valleys) will have a more dramatic effect on most animal populations than maintaining a mosaic of even-aged stands in different seral stages (the stages of plant community and ecosystem development following the disturbance of a site through to the re-establishment of the pre-disturbance vegetation condition). Uneven-aged forest management that maintains a continuous tree cover on a site will generally cause less change in the animal community than clearcutting. This will favour mature-forest animal species and dis-favour animals adapted to disturbance.

e) Microbes and soil animals are sensitive to the effects of timber harvesting because they depend largely on live or recently dead plant roots or fresh above-ground litterfall as an energy source. There is normally a considerable change in the composition of the microbial community and of the soil fauna following clearcut harvesting because it causes a change in the quantity and quality of the litterfall. This is generally associated with a period of accelerated decomposition rates and increased nutrient availability. Uneven-aged harvesting systems result in less change in soil fauna and microbes. Microbial and soil faunal communities will return to pre-harvesting abundance and species composition as succession proceeds back towards the original forest condition.

6. Timber harvesting can impact a number of non-timber resource values, including wildlife, fish, water, recreation and wilderness. These impacts can be either positive or negative. Frequently, only the negative effects receive media attention.

For many species of animal, the benefits of harvesting that is conducted with a sensitivity to their habitat requirements will outweigh the negative effects. The net effects will probably be negative for old growth-dependent species, and may be negative where large areas are clearcut over a short period of time, or where there are prolonged delays in reforestation. Most impacts of forest harvesting on fish habitat, where they occur, are negative, although stream warming may sometimes be beneficial, and the input of large woody debris to some streams may improve fish habitat by creating pools. Timber harvesting conducted with a sensitivity to fish habitat and streams need have little or no negative effects on these values. Most impacts on water quality, where they occur, are also negative, but these are generally short lived. Some effects may be positive, such as short-term nutrient enrichment of nutrient-poor streams and lakes. There have certainly been cases in which clearcut logging in water supply

areas has created short-term water quality problems, or problems with the timing of snowmelt or timing of streamflow. However, there are far more examples in which careful forest harvesting, including clearcutting, has had no measurable negative effects on watershed values. Negative impacts are more a function of the percentage of a watershed that is harvested at one time and the care with which the harvesting is planned and conducted. Once again, roads are generally responsible for most of the negative impacts on water quality.

Forest recreation can benefit from the access to remote areas and to subalpine/alpine environments provided by logging roads. Most of the recent media coverage of harvesting/recreation interactions has been negative, however. Too much access to remote areas can lead to site damage (eg. in subalpine and alpine meadows) or reduced quality of the recreational experience for those who value solitude and "low-technology" recreation. Similarly, forest harvesting in British Columbia has often been insensitive to the visual alterations it causes in the landscape, and to the albeit short-lived ugliness of many recently clearcut harvested areas. Some of the conflict between forestry and the environmental movement could have been avoided if more attention had been paid over the past two decades to "landscape architecture", visual resource management, and measures to minimize the visual impact of forest harvesting on recreationists. This would not have solved the problems that improved access sometimes causes by increasing hunting pressure and allowing access by all-terrain vehicles to sensitive areas.

Much of the negative impact of timber harvesting on aesthetics is temporary. The visual quality of the environment is restored as the forest regrows. Where regrowth is prevented or delayed by soil damage caused by roads and skid trails, the visual damage will be much more persistent. In most cases, the visual damage caused by harvesting is a short lived land-use issue, not an ecological or environmental issue. The environmental issues associated with improved access are much more permanent.

It should also be noted that the general public concern about the aesthetics of logging is relatively recent. It is inappropriate to hold foresters accountable for harvesting conducted twenty to thirty years ago that is now deemed to be aesthetically unacceptable, when the majority of the society at that time accepted the practice and there was no legal or managerial requirement to conduct harvesting in anything but the prevailing manner. However, foresters are accountable for the present and future aesthetic implications of timber harvesting.

7. Wilderness and old growth issues must be a part of the evaluation of timber harvesting. The province cannot afford a continuing drain from its productive forest land base of set-asides for wilderness recreation and old-growth reserves. Yet the public

has the right to expect an adequate supply of such areas on public land to satisfy the growing demand for recreation and the need for ecological reserves. Clearly the conflict between maintaining the land base for timber production and designating such lands for alternative uses in one of the key forestry issues in the province today. There is an urgent need to produce a provincial master plan that identifies the lands that will be dedicated in perpetuity to timber production, recreation, research, education, ecological reserves, and other uses (hydro, roads, agriculture, etc).

Old growth values are not sustained under the current strategy of timber management, but it should be possible to recreate many of them following timber harvesting using an appropriately designed silvicultural and management system. The concept of "pocket wilderness" surrounded by areas of productive forest grown on long rotations to create old growth values should be re-examined. There is little question that more old growth reserves will be created. Their selection should be based on the need to complete the province's system of ecological reserves, and the distribution of recreational reserves should reflect the geographical distribution of the recreational demand. Management zoning to address this variety of needs must be developed.

8. Many of the concerns about the impacts of timber harvesting will pale in comparison to the potential consequences for our forests of the widely predicted global climate change. The time is probably not too far away when all industrial and individual activities will have to be examined for their impact on the concentration of atmospheric "greenhouse gases" and global warming. Timber management that conserves soil structure, organic matter and nutrients, maintains or enhances forest productivity with minimum fossil-fuel-dependent technological inputs, and produces permanent or long-lived end products (eg. lumber) will provide a net sink for atmospheric carbon dioxide (CO_2). This will help to reduce the problem of climate change. Forestry that lowers site productivity, reduces soil organic matter and nutrient levels, depends on heavy inputs of fossil-fuel-based technology, and/or produces "throw-away" end products will make the "greenhouse problem" worse.

Productive, sustainable timber management producing long-lived wood products is thus part of the "greenhouse solution". Exploitive forestry that damages soil productivity, or forestry that reduces the storage of carbon in the ecosystem without producing long-lived products can be a part of the "greenhouse problem". However, compared with tropical deforestation, global fossil fuel use and global cement production, the net contribution of B.C. forestry to the "greenhouse problem", either positive or negative, will be small. The fact that all these sources of CO_2 release only contribute 50% of the "greenhouse problem" (the other 50% is methane, ozone, chlorofluorocarbons, and other gases) further reduces the significance of the carbon budget of B.C. forestry in

the global warming equation. This in no way reduces the importance of making B.C. forestry part of the solution to global warming, but sets it in perspective.

9. Clearcutting has been railed against by most environmentalists who have claimed that it "destroys the environment". However, when practised correctly, clearcutting is an ecologically sound and sustainable method of timber harvesting for the appropriate species on the appropriate soils in the appropriate climates. It is the major timber harvesting system used around the world and is widely used in Scandinavia and Europe. In Sweden there is a legal requirement to clearcut forests based on fifty years experience which demonstrated that alternative harvest systems resulted in a reduction in many of the values of the forest ecosystem. Other harvesting systems are used, or should be used where silviculturally appropriate, in hot dry climates or dry sites, on steep unstable slopes, in protection forests, on recreationally-important, visually-sensitive landscapes, in some subalpine forests, and in other special situations that require the maintenance of continuous forest cover on a site.

A major problem of clearcutting in B.C. in the past has been a frequent insensitivity on the part of most forest companies and, until relatively recently, the Ministry of Forests toward the aesthetic aspects of clearcut harvesting and associated roads. In some areas soil damage has been just as important or even more important a consequence of harvesting than visual damage because the latter is generally much more temporary than the former. Similarly, where clearcutting in the past has caused wildlife and stream/fish problems, these have often been more significant and permanent than the visual damage. However, in many of the conflicts over clearcutting, it has been the visual alteration of the landscape that has so upset the general public. Frequently, the most serious and persistent examples of visual damage associated with timber harvesting have been caused by road construction.

Whether or not clearcutting is the appropriate timber harvesting method will depend on the objectives of forest management, the climate, aspect and slope of the site, the ecological requirements for regeneration of desired tree species, and a variety of other ecological factors. The acceptability of clearcutting also depends on the size, shape, orientation, spatial relationship to previous and future cuts, and the visibility of the cut. Harvesting systems must be used that are appropriate for each type of crop tree on each type of site within each particular biogeoclimatic zone or subzone. They must be designed to sustain both timber and non-timber resource values, regional biological diversity, local employment, and community stability. In many cases, even-aged management with clearcutting is the silvicultural system of choice by which to satisfy these diverse land-use objectives. In some situations, different systems would be more appropriate, and there

are some areas of the province where the traditional practice of clearcutting should probably be replaced by other systems. In most cases, careful shaping, orientation, and location of smaller clearcuts will satisfy many of the objections that the public has had to clearcutting. Above all, decisions about clearcutting as alternative systems must be site-specific and must reflect the ecology of the site in question.

10. A major shortcoming in B.C. forestry that is believed to have contributed to the seemingly endless conflicts between timber harvesting, other forest-based resources, and concerned citizen groups is the lack of an adequate forest management planning framework. Without specific and explicit planning goals with respect to all resources of concern, timber harvesting has lacked appropriate performance standards and has not been adequately integrated into the rotation-length crop production cycle and integrated landscape management of which it is a part. The lack of specific planning goals is partly because timber management planning in British Columbia has been isolated from management planning for other forest-based resources such as water, wildlife, fish, and recreation. Until forests are managed under integrated plans that are specific to the ecology, markets, economics, and social needs of the forest area to which the plans apply, it is likely that conflicts between timber harvesting and other forest users will continue.

Monitoring of performance, of conformity with existing regulations, and of environmental impacts has been inadequate, both because of lack of resources provided to the monitoring agencies, and because of the lack of government policy that ensures that this be done. Recent harvesting guidelines have focused on some of these problems, and the institution of the Pre-harvest Silvicultural Prescription and of guidelines concerning logging and streams and logging and wildlife should reduce the frequency of unacceptable timber harvesting impacts in the future. But there is still a need to develop, and ensure the implementation of, a comprehensive and ecologically-sound set of integrated forest management objectives and guidelines. Another problem associated with timber management planning is the lack of sensitivity of the currently-used planning tools to management-induced changes in long-term site productivity. These planning tools are also insensitive to the consequences for forest growth and yield of the widely-predicted global climate change.

11. A fundamental issue that must be addressed by the forestry profession is the pervasive lack of understanding by the general public about forestry, its environmental impacts, and its economic and social importance in British Columbia. The environmental movement has been successful in raising the public consciousness about forestry, and this is a good thing. It has created the political climate in which much needed improvements in forest management can be made. Unfortunately, much of what is said by

some of the more vocal environmentalists about timber harvesting is inaccurate, incomplete, or out of context. Generalizations are often made that are only true under certain circumstances. These inaccuracies are of less concern during the "political phase" of conservation than during the "implementation phase", when policy and regulations must be developed by which the desired improvements can actually be achieved. Greater efforts must be made to engage environmentalists and other members of the public in on-the-ground experiences by which they can gain a more accurate understanding of forestry and its environmental impacts. Unless this is achieved, their efforts may hinder rather than help to achieve better management of British Columbia's single most important resource. Public education about forestry must become a priority, but accompanying this there must be an improvement in the quality of forest management. Increased use should be made of demonstration forests located near to urban cities. These should demonstrate state-of-the-art, ecologically sound management practices to foresters and the public.

12. Timber harvesting can impact the native peoples of British Columbia in a variety of ways. It can provide local employment, and it can increase the abundance of certain wildlife species used for food. However, harvesting may disrupt trapping of species that are dependent on mature forest or old-growth, it provides access for non-natives who may compete for the wildlife resource, and it may have a negative impact on a variety of spiritual and traditional life-style values. More attention should be paid to the impacts of timber harvesting on the native peoples, who should have input to the forest management planning process.

13. This discussion paper focuses mainly on the local, ecosystem-level impacts of timber harvesting. This is only half of the problem. Many of the conflicts between timber harvesting and other forest users are the result of the rate at which B.C.'s forests are being harvested, and the spatial distribution of harvesting in the landscape. Topics such as the "fragmentation" of areas of old-growth, the rate at which particular watersheds or valleys are being harvested, and the sustainability of current harvest levels are attracting increasing attention from the public. The issues addressed in the present paper are complementary to these "whole-forest" issues. All these issues must be addressed in a comprehensive, integrated manner if we are to achieve truly sustainable development of our forest resources.

ACKNOWLEDGEMENTS

The following individuals kindly consented to review a draft of this paper. Most of their comments and suggestions have been incorporated. Errors and omissions in the report remain the author's responsibility, however.

Drs. Gordon Weetman (Professor of Silviculture, U.B.C.), David Haley (Professor of Forest Economics, U.B.C.), and John Nelson (Assistant Professor of Forest Harvesting, U.B.C.); Drs. Phil Haddock (Emeritus Professor of Silviculture, U.B.C.: B.C. Federation of Naturalists), Bert Brink (Emeritus Professor of Range Ecology, U.B.C.: B.C. Federation of Naturalists), Ken Lertzman (Assistant Professor of Resource Management, Simon Fraser University), Bristol Foster (Environmental Consultant: ex-Director of the Provincial Museum, Victoria: ex-Director of B.C.'s Ecological Reserves Program), and Juergen Hansen (Research Scientist, Agriculture Canada, Similkameen Parks Association); Messrs Gerry Burch (R.P.F., consultant; retired company Chief Forester), Trevor Jeans (R.P.F., consultant; retired company Chief Forester), and Bill Young (R.P.F.; retired Chief Forester, B.C. Ministry of Forests).

I would like to thank Mrs. Betty Campbell, B.C. Forest Resources Commission, for her patience, and typing through the many drafts of this paper. Also, my wife, Ann, who ran her critical editorial eye over the manuscript.

TABLE OF CONTENTS

EXECUTIVE SUMMARY..... i

ACKNOWLEDGEMENTS..... x

TABLE OF CONTENTS..... xi

TABLE OF CONTENTS - FIGURES..... xiii

1. INTRODUCTION..... 1

2. ECOLOGICAL CONSIDERATIONS IN FOREST HARVESTING 6

2.1 The Forest Ecosystem and Its Functional Processes... 6
2.2 Temporal Dynamics of Forest Ecosystems: Change Over Time..... 11
2.3 Other Aspects of Forest Ecosystems..... 16
2.4 Stratification of the Ecological Variability of B.C.'s Forests..... 17
2.5 Variations in Biological Diversity Following Disturbance..... 18
2.6 Successional Considerations in Forest Harvesting.... 23
2.7 Conclusions..... 24

3. A SHORT PRIMER ON FORESTRY..... 26

3.1 Introduction..... 26
3.2 The Objectives of Management and Their Achievement Through Management Planning..... 27
3.3 Organization of Timber Management..... 30
3.4 Regional and Local Aspects of Sustained Yield..... 34
3.5 The Tree Crop Production Cycle: Silvicultural Systems..... 37
3.6 Conclusion..... 43

4. TECHNICAL CONSIDERATIONS IN THE SELECTION OF A FOREST HARVESTING METHOD..... 44

4.1 The Role of Markets and Product Values in Determining Silviculture..... 44
4.2 Factors Affecting the Choice of Harvesting System... 45
4.3 Types of Harvesting Equipment..... 48
4.4 Roads and the Environmental Impact of Harvesting.... 51
4.5 Conclusions..... 52

5. ECONOMIC CONSIDERATIONS IN THE SELECTION OF THE METHOD OF FOREST HARVESTING..... 54

5.1 Relative Costs of Harvesting by Different Methods... 54
5.2 Economics of Second Growth Harvesting in Comparison to the Harvesting of Old-Growth and Previously Unmanaged Forests..... 56

6. FOREST HARVESTING AND ENVIRONMENTAL CONCERNS..... 62

6.1 Impacts on Soil..... 62
6.2 Effects on Microclimate..... 67
6.3 Effects on the Biota..... 68
6.4 Ecosystem Recovery from the Impacts of Harvesting... 70
6.5 Closing Statement..... 72

7. IMPACTS OF FOREST HARVESTING ON SPECIFIC RESOURCE VALUES..... 73

7.1 The Timber Resource..... 73
7.2 Wildlife..... 75
7.3 Fish and Water..... 77
7.4 Range..... 79
7.5 Recreation..... 79
7.6 Wilderness..... 80
7.7 Conclusion..... 81

8. HARVESTING AND THE OLD GROWTH ISSUE..... 83

9. HARVESTING AND CLIMATE CHANGE..... 85

10. THE CLEARCUTTING ISSUE IN BRITISH COLUMBIA..... 89

10.1 Timber Harvesting Around the World..... 89
10.2 Clearcutting in British Columbia..... 91
10.3 Predicting the Long-term Consequences of Alternative Forest Harvesting Strategies..... 94

11. IMPACTS OF HARVESTING ON THE NATIVE PEOPLE OF B.C..... 95

12. SUMMARY AND RECOMMENDATIONS..... 96

TABLE OF CONTENTS

FIGURES

2.1 The Three Major Cycles of the Forest Nutrient Cycle..... 10

2.2 Factors That Determine the Capture of Solar Energy..... 12

2.3 Diagrammatic Representation of the Series of Seral Stages..... 14

2.4 Variation in Ecosystem Productivity..... 15

2.5 Variation in Ecosystems Along a Minor Topographic Sequence..... 19

2.6 Variations in Tree Species Diversity in B.C..... 21

2.7 Diagrammatic Representation of the Concept of Ecological Rotations..... 25

3.1 Diagrammatic Representation of the Age-class Structure of an Even-aged "Normal" Forest..... 31

3.2 Diagrammatic Representation of the Age-class Structure in an Even-aged Forest With 3 Cutting Cycles..... 33

5.1 Relationship Between Logging Costs and Six Factors that Affect the Economics of Logging..... 57

TABLES

5.1 Average Costs of Yarding in Coastal and Interior B.C..... 58

5.2 General Relationship Between Cost of Yarding a m^3 of Log and the Size of Log..... 59

5.3 Comparison of the Costs for Various Phases of Harvesting Between Helicopter and "Conventional" Logging..... 60

5.4 Detailed Breakdown of the Costs of Typical Coastal Harvesting..... 61

CHAPTER 1. INTRODUCTION

Most forms of renewable resource management involve the harvest of a product, be this water or electricity from a hydro impoundment, food from farms, or timber, forage and wildlife from forests. But the profession of forestry is no more limited to harvesting trees than farming is limited to harvesting grain or beef; harvesting is simply the final stage in the cycle of renewable crop management. Harvesting trees is the culmination of the silvicultural system by which tree crops are produced to satisfy society's need for building materials, paper and packaging products, renewable bioenergy, synthetic chemicals made from wood, and various other materials. Where the forest has been previously unmanaged and unharvested, timber harvesting initiates the crop production cycle that leads to the subsequent harvest.

The public of British Columbia generally accepts crop harvesting in agriculture. In contrast, there is great dissension over the harvesting of trees in the province's forests. Whereas the public understands the relationship between the food they buy and agricultural harvesting activities, the relationship between building a house or reading a newspaper and timber harvesting is not so widely understood. There are many reasons for this difference in attitude. Agricultural systems are a widely accepted human "artifact" in the landscape; most of B.C.'s forests are still "natural". Most harvested food crops regrow the next year; forest tree crop regrowth may take up to a century, or even more in some northern and high elevation environments. Re-establishment of native forest or old-growth values may take two or more centuries, although it can take much less time than this. Harvested fields often appear to be tidier and more organized than a forest clearcut, and the visual impacts of harvesting on a farm are short-lived compared to the visual recovery of a clearcut forest. The harvesting of trees can have an impact on far more non-crop resource values than does an agricultural harvest; wildlife, fish, water, and forest-based recreation are more intimately connected to and affected by the structure of the forest than is the case with an agricultural crop. Many forests are located on steep, highly visible, and potentially erodible mountain slopes, whereas most agriculture is on flat land, is less prone to some types of soil loss, and is generally less visible to the average citizen. The list could go on.

About 95% of the forested land in British Columbia is publicly owned. In a democracy, it is the will of the people, acting through the political process, that ultimately decides questions of land use, the permissible environmental impact of industrial activity, and the constraints that are placed on free enterprise. The "Tragedy of the Commons" is now a widely recognized principle: that without adequate regulation, individuals or individual organizations operating in a common or public resource will generally act to optimise their personal benefit, and that this

almost inevitably results in a collective detriment. The "commons" of air and water have been widely abused in the absence of adequate regulations, or enforcement of regulations, as industries have externalized their waste-control costs by using the atmosphere and water bodies as a dumping ground for their waste products. Municipalities have behaved in much the same way, with their sewage and garbage disposal practices. Similarly, forest companies operating in the "commons" of B.C.'s publicly-owned forest land, generally with inadequate incentives, regulations, or directives by the government to ensure adequate "protection of the environment", have often externalized their costs of log production.

In the past there has been insufficient investment in regeneration, many cases of inadequate road construction and maintenance, soil damage through careless or inappropriate logging practices, and damage to streams, certain wildlife values, and the aesthetics of the landscape. It is not in the least surprising, therefore, that forestry in British Columbia is receiving increasing attention from a certain sector of a society which is becoming increasingly concerned about environmental quality, human-induced global climate change, "acid rain", and loss of biological diversity. It is inevitable that this sector of the public will try to pressure its elected politicians to restrict what is widely perceived to be the "environmental destruction" caused by timber harvesting, which is widely regarded by many members of the environmental movement as being synonymous with forestry.

There is little doubt that the political action of concerned citizens' groups around the world has been instrumental in limiting industrial pollution, the loss of biological diversity, and the degradation of agricultural soils. The political activities of such groups have also contributed significantly to improvements in the practice of forestry. Many of the positive changes in forest practice and management in our province over the past two decades had their origins in the local concerns and lobbying activities of naturalists, parks associations, professional groups, and miscellaneous other concerned citizen groups. The recent FRDA program to improve the overall condition of Canada's forests was stimulated by the action of concerned professional foresters. However, in as ecologically-diverse an area as British Columbia, with its wide range of climates, soils, topography, vegetation, wildlife species, and human communities, there is a significant risk attached to the regulation of forestry by lobby and political action groups unless this is balanced by appropriate technical and scientific inputs. Democracy only works well when the public is well-informed about the issues of concern. Regrettably, much of the public pressure for change in forest practice in British Columbia is not adequately grounded in an understanding of the geography, ecology, pedology and economics of the forest resource or of the objectives and techniques of forest management. In the absence of this understanding, the public is forced to make

generalizations, many of which are only accurate in certain specific locations, or under certain specific circumstances. It is unlikely that workable and effective conservation strategies can be developed from public inputs if these are socially and economically unrealistic, and scientifically inaccurate.

The history of forestry around the world is replete with examples of the failure of forest management to achieve its goals when it was organized and conducted under rigid regulations, dictates, or laws that did not recognize the temporal and spatial variability of forests, the structural and functional complexity of the forest ecosystem, the critical importance of soil and soil microorganisms, and the inevitable characteristic of ecosystem change over time. Many of the failures in B.C. forestry have similarly been the product of the rigid application of rigid regulations that were developed before the need for an ecological approach to forest management was recognized and accepted. In reviewing the whole question of timber harvesting in British Columbia, and public attitudes thereto, the Forest Resources Commission should be mindful of this history, should recognize the complexities posed by the geography, ecology, and sociology of the province, and should be aware of the need for site and situation-specific evaluations and harvesting guidelines.

British Columbia is one of the most ecologically diverse landscapes of comparable size anywhere in the world, and this makes forestry in B.C. much more complex than in ecologically simpler areas like New Zealand, Sweden, or the south-eastern U.S. Many of the problems facing B.C. forestry today are a result of the failure of "foresters" in the earlier days of B.C. forestry to modify their practices as they moved from one type of forest landscape to another. This was largely because B.C. forestry in the early days was dominated by forest harvesters, who were often engineers and not biologically-trained foresters. Silviculturally-oriented foresters were frequently powerless to control the methods and patterns of harvesting, despite vocal opposition to practices that they felt were inappropriate. It would be ironic if citizens concerned about the environment made the same mistake by calling for rigid, unvarying, and ecologically-insensitive controls on the practice of forestry in British Columbia, particularly since forestry in the province has recently been placed on a sound ecological foundation (the biogeoclimatic land classification system), and since silvicultural foresters are gaining an increasingly influential role in forest management decision making.

The Commission should recognize that many of the recent failures of the Ministry of Forests to ensure that the level of forest management in the province is acceptable are directly attributable to major reductions in Ministry funding and staffing in the 1980's. In spite of the Ministry's adoption of an ecological foundation for silviculture, they have frequently lacked the resources to ensure the implementation of, and compliance with, this ecological

basis for forest management. The growing public opinion that the Ministry should be more involved with the regulation of management is in conflict with the government's policy to "privatize" and reduce the Ministry's involvement. This complex topic is not explored here, but should be noted.

The objective of this discussion paper is to provide the Commission with a review of some of the ecological, technical, economic, and social considerations in the selection of methods by which to harvest the tree component of a forest ecosystem. The paper will also discuss a number of environmental concerns and public issues related to timber harvesting. It will conclude with a comment on timber harvesting practices in some other parts of the world, a brief chapter devoted specifically to the issue of clearcutting, and a set of recommendations with respect to tree harvesting and the associated silvicultural systems for British Columbia. The paper does not address the issue of the current rate of cut and the alleged overcutting relative to the prevailing levels of management. The rate of cut for the province does have a number of important social and environmental implications, of course, but the paper focuses more on the local site aspects of harvesting.

The paper is somewhat longer than was originally intended. Yet it scarcely scratches the surface of most of the topics it addresses. Evaluation of the impacts of timber harvesting in as complex a land unit as the Province of British Columbia is a formidable undertaking. It requires a substantial body of knowledge concerning the bio-physical character and variability of the resource, and the objectives and techniques of resource management. Because of the diversity of background of the members of the Forest Resources Commission, I decided to err on the side of inclusion rather than omission of topics. Not all Commission members will find it necessary to read all the chapters of the paper. The following is a brief guide to the content of the various chapters.

Chapter 2, Ecological Considerations in Timber Harvesting, is a brief "primer" on forest ecology. It provides an ecological background for those Commissioners who may lack such knowledge. Ecological processes and the impacts of harvesting thereon are referred to throughout the paper. Those Commissioners familiar with ecology may chose to omit this chapter.

Chapter 3 provides a similar primer on some of the broader aspects of forest land management and timber management. It deals briefly with forest management planning, annual allowable cuts, sustainability, and the silvicultural cycle. Those Commissioners familiar with forestry will probably choose to omit this chapter. For those unfamiliar with a variety of silvicultural and management terms that are referred to in other chapters, it provides both definitions and a context within which to judge timber harvesting.

Chapter 4 reviews some of the technical considerations that

determine the choice of harvesting system, briefly defines various different types of harvesting equipment, and reviews the role of roads in timber harvesting and the impact of forest roads on the environment.

Chapter 5, briefly draws attention to some economic considerations in timber harvesting.

Chapters 6 & 7, perhaps the heart of the report, consider the impacts of timber harvesting on various aspects of the forest ecosystem, and the general classes of impacts of harvesting on specific resource values.

Chapters 8 & 9 examine the issues of "old growth" and global climate change as they relate to timber harvesting. These may be considered as peripheral issues, but I believe that they should be part of the Commission's background.

Chapter 10 attempts to dispel the myth that clearcutting is inevitably environmentally destructive. It examines the practice of clearcutting around the world and in British Columbia and contrasts it with alternative methods. This section is really a synthesis of the other sections because the timber harvesting issue in British Columbia is really the issue of clearcutting.

Chapter 11 makes brief reference to the impacts of timber harvesting on the native peoples of British Columbia.

The paper concludes with a summary of the technical issues that have been covered in the paper and some recommendations. Appendices are provided that contain a copy of the Ministry of Forest's biogeoclimatic zone map for the province, a copy of an encyclopedia yearbook article on old-growth, and copies of several papers on the type of ecosystem management model that should be used to predict the long-term consequences of alternative harvesting methods.

CHAPTER 2. ECOLOGICAL CONSIDERATIONS IN TIMBER HARVESTING[1]

There is a widespread public misunderstanding about, and concern over, the ecological impacts of timber harvesting (hereafter also referred to as "logging"). This concern is certainly justified. There have been in the past, and continue to be, far too many examples in which timber harvesting has resulted in damage to one or more of the several resource values provided by a forested landscape. But if this concern is to be translated into policy and regulations that are effective in achieving better management of our forests, it must be informed concern that is based, first and foremost, on an understanding of the consequences of timber harvesting for the form, function, and temporal dynamics of the forest ecosystem. This section of the paper provides a brief review of those aspects of forest ecology that should be understood by anyone evaluating the impacts of timber harvesting.

2.1 The Forest Ecosystem and It's Functional Processes[2]

a. Energy in Ecosystems

A forest is an ecosystem: a complex system of interacting components and processes. It is comprised of an assemblage of plants, animals and microbes, interacting with a soil and a regional climate. It has a microclimate that is created primarily by the vegetation, and a local climate that is largely a function topography, elevation, aspect, and the regional climate. It's topographic features determine many of the characteristics of the soil.

In common with most other types of ecosystem, a forest ecosystem is powered by the solar energy that is captured by the process of photosynthesis. The magnitude of photosynthetic production (net primary production), and hence the productivity of the ecosystems, is determined by the magnitude and efficiency of the forest's photosynthetic apparatus: its foliage. Up to a certain point, the greater the mass or surface area of leaves, the greater the capture of energy by the forest. In a closed forest, most of the leaves are tree leaves, so most of the photosynthate produced is allocated to tree growth. In a more open forest, or a clearcut, much of the leaf area is accounted for by herbs (grasses and forbs), shrubs, and non-commercial trees. As long as there is an

---

1 The term "forest harvesting" is often used as a synonym for "timber harvesting". However, other resources can be harvested from forests: wildlife, mushrooms, berries, foliage, bark, to name a few. This report is concerned with the harvesting of the tree component of the forest.

---

2 For more details about the ecology of forests, see Kimmins, J.P. 1987. Forest Ecology. MacMillan, NY. 531 pp, or some comparable volume.

equivalent leaf area, the capture of solar energy by this more diminutive vegetation may not be very different to that captured by the more physically imposing forest. However, herbs and shrubs tend to allocate more of the solar energy they capture to organs that are short-lived (eg. leaves), and therefore they do not accumulate as much of the energy in permanent tissues (like woody stems) as do long-lived trees. Consequently, they do not grow as large.

Energy captured and stored by plants may be available to one of the many species of herbivore (a plant-eating animal) that live in the forest. Foliage is a more favourable source of food energy for many herbivorous animals than are the various types of woody tissues in the forest. For ground-based animals, the foliage of herbs, shrubs, and young trees is physically more available than the foliage of larger trees, and is generally more palatable and nutritious. Consequently, a much higher percentage of the energy captured by herbs and shrubs is passed on to herbivores than is the case for trees, except in the case of outbreaks of defoliating insects. Well-vegetated clearcuts, and forests with significant gaps in the canopy and a well developed understory, have a high carrying capacity for most ground-based herbivorous animals. In comparison, most of the leaf area in a dense forest is high up in the canopy of the trees and the leaves are frequently less nutritious. Consequently, such forests will have a lower carrying capacity for these animals. The nutritional importance to some large ungulate herbivores of lichens that grow in the canopies of large old trees should not be overlooked, however. These lichens become available when branches are broken by snow or wind and fall to the ground.

The annual death of ephemeral plant tissues (eg. fine roots, old leaves of conifers, the entire foliage of deciduous species), the death of trees due to competition for light, disease, or other mortality factors, and the death or defecation of animals transfers energy to the third major functional group of organisms in the ecosystem: the decomposers. Fungi and bacteria are responsible for much of the biochemical activity that ultimately disassembles the complex high-energy molecules that were constructed by photosynthesis and subsequent plant metabolism. But these micro-organisms generally operate in partnership with a diversity of soil animals which act to physically prepare dead plant and animal material for microbial decomposition, or which ensure that micro-organisms are continually brought into contact with newly dead plant and animal organic matter.

The energy that powers ecosystems is the chemical energy of complex organic molecules. The assembly of these molecules requires a supply of an appropriate mixture of chemical elements: the macro- and micro-nutrients. Forest productivity, whether it be the growth of trees, the increase in abundance of wildlife, or the production of mushrooms, thus requires an adequate supply of

various nutrient elements, the relative abundances of which satisfy the nutritional requirements of the various plant, animal, and microbial species.

b. **The Chemistry of Energy Transfers and Storage in Ecosystems**

Energy enters ecosystems by the process of photosynthesis, is temporarily stored in biomass, and is lost again in the process of respiration as organisms use the chemical bond energy of organic molecules to power their metabolism. This energy is not recycled or reused, but because of the relatively unchanging and inexhaustible supply of energy from the sun, it is "renewable". The nutrient elements that are involved in energy capture and storage are less renewable, but are recycled and reused. To understand the impact of forest harvesting on ecosystem function requires an understanding of the basic processes of nutrient cycling, a subject that is referred to as forest biogeochemistry.

There are three major pathways of nutrient dynamics in the forest ecosystem: 1. additions and losses of nutrients to and from the ecosystem (the geochemical cycle); 2. circulation of nutrients between plants, animals, microbes and the soil within a particular ecosystem (the biogeochemical cycle); and 3. the internal conservation of nutrients within organisms, which reduces losses of nutrients from individual organisms (the internal or biochemical cycle) (Figure 2.1).

The geochemical cycle consists of nutrients added to the ecosystem in rain, snow and dust, nutrients released into the soil by chemical weathering of bedrock or of rock minerals in the soil, and nutrients carried into a downslope ecosystem by water flowing down from upslope ecosystems. Uptake of atmospheric carbon dioxide (CO_2) in the process of photosynthesis, uptake of gaseous ammonia (nitrogen) and oxides of sulphur from the atmosphere by foliage, and fixation of atmospheric nitrogen gas by "nitrogen-fixing" organisms are other important geochemical inputs. Additions of fertilizers or of nutrients in the feces or dead bodies of animals moving into the area can sometimes be an important input. Losses of nutrients from the ecosystem constitute geochemical outputs. These include losses in harvested materials, by soil leaching and erosion, due to fire (gaseous and flyash losses to the atmosphere), by the migration of animals, and through the release of CO_2 by respiration, nitrogen by denitrification, and various other gaseous losses.

The geochemical cycle is important because the balance between geochemical inputs and outputs determines the inventory of nutrients in the ecosystem, and, as noted above, this inventory is related to energy capture and storage. Relatively small annual inputs over a tree crop rotation may compensate for relatively large but infrequent outputs that can accompany forest harvesting

or natural disturbance (eg. wildfire). The geochemical inputs are thus responsible for maintaining long-term site productivity and for assisting in the recovery of the ecosystem from disturbance.

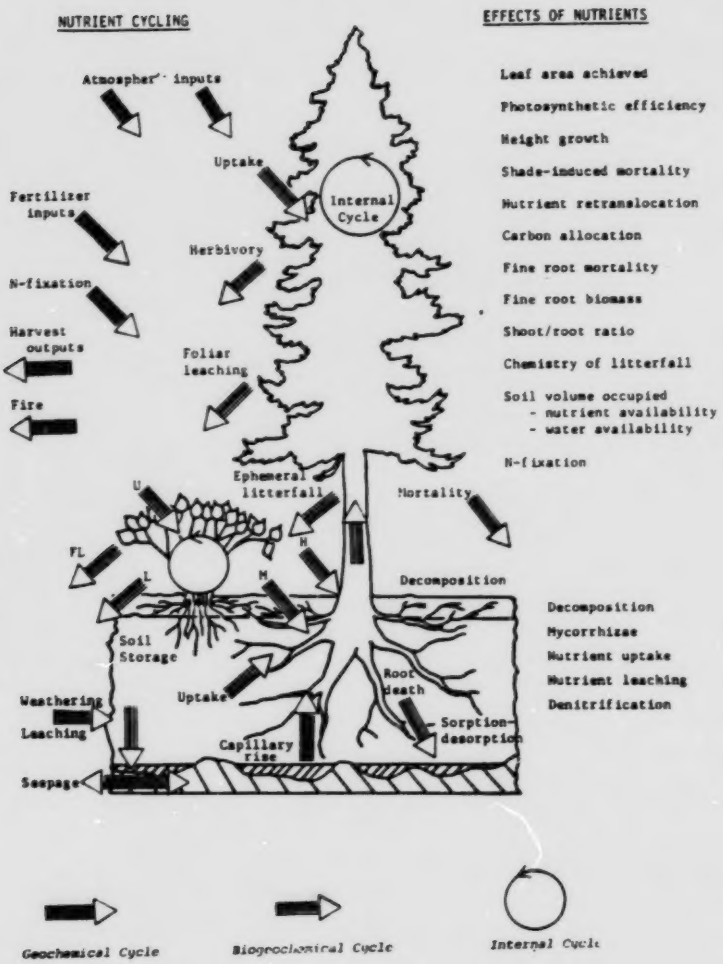
The biogeochemical cycle is more closely related to short-term and medium-term than to long-term forest productivity. The rates of various processes within this cycle, especially the rate of decomposition of organic matter, determine the availability of nutrients in the soil for uptake by trees and other plants. This availability is a major determinant of the biomass and photosynthetic efficiency of the foliage (Figure 2.2), and thus of forest productivity. If the circulation of nutrients in this cycle is slow (eg. in cold, northern forests), forest growth may be slow in spite of the large inventories of nutrients present in the slowly-decomposing forest floor. Forests in which litter decomposition and nutrient circulation in the biogeochemical cycle are rapid (many tropical rain forests) may have high levels of photosynthesis and productivity in spite of rather low inventories of nutrients in the soil.

The third cycle reflects the internal conservation of nutrients within an organism. Plants work hard (i.e. produce lots of roots and allocate a large portion of their photosynthate) to obtain soil nutrients. Where the availability of nutrients is low, plants will reduce their nutrient losses as well as trying to increase their uptake. For example, nutrients which are in short supply are removed from leaves before they fall, and from stem sapwood before it dies and becomes heartwood. More than half of the nutrients required to produce new leaves, bark, sapwood, etc. may be provided by this internal reallocation of nutrients within a tree growing on a nutrient-poor site. Internal recycling can help to smooth out season-to-season or even year-to-year variations in soil nutrient availability. It can also help trees which are efficient at internally recycling nutrients to grow remarkably well on relatively nutrient-poor sites. Plant species which lack this ability may be excluded from such sites. Internal cycling can temporarily help to maintain the level of plant growth as soil becomes impoverished in nutrients, but eventually a long-term decline in soil fertility will be accompanied by a decline in growth.

Where the availability of nutrients in the soil is low, plants will increase their allocation of photosynthate to the production of fine roots. It is all a question of balance. If the foliage can get more light and carbon (as CO_2) from the atmosphere than nutrients (especially nitrogen) and/or moisture from the soil, a plant's "best bet" is to put its growth effort into finding more soil nutrients and moisture. On a moist, fertile site, however, soil nutrients and moisture may be more available than atmospheric CO_2 and light, so the plants put more effort into foliage

Figure 2.1

The three major cycles of the forest nutrient cycle: the geochemical, the biogeochemical and the internal or biochemical cycle. The wide variety of effects that nutrient availability has in the ecosystem is listed to the right of the figure.



production and stem height growth. This "resource allocation" strategy is particularly sensitive to soil nutrients, and thus to the biogeochemical cycle, although it is also sensitive to light and soil moisture (Figure 2.2). Because changes in resource allocation have such a major effect on the rate of accumulation of useable stem wood, and because resource allocation is so closely related to nutrient availability, a knowledge of forest biogeochemistry is very important in timber management.

2.2 Temporal Dynamics of Forest Ecosystems: Change Over Time

Few things are as certain as death, taxes and change. With very few exceptions, the forests of the world are undergoing continual change. The major reason for this is the process of natural succession by which an ecosystem recovers through a series of "seral stages"[3] back to its original condition following some disturbance event. In most forest ecosystems, disturbance is frequent enough that the ecosystem is always in some stage of recovery. However, if the frequency of disturbance is low, or if the ecosystem recovers very rapidly, then the ecosystem may achieve a final, relatively stable terminal seral stage called the "climax". In this condition, the small-scale disturbance caused by the death of individual large old trees leads to their replacement by seedlings of the same species.

In true climax forests, the species are self-replacing, at least until the next major disturbance which initiates a new series of recovery stages. The number of stages on the return to the climax condition will depend upon how severely the ecosystem has been disturbed. In the most extreme cases (eg. catastrophic wildfire, extremely severe slashburning, massive soil erosion), virtually all living things and dead organic matter are lost, mineral soil is removed or destroyed[4], and succession begins in a relatively harsh, inorganic environment (primary succession). There are usually several and maybe many seral stages in the recovery of such a severely disturbed ecosystem, and the process may take as long as

---

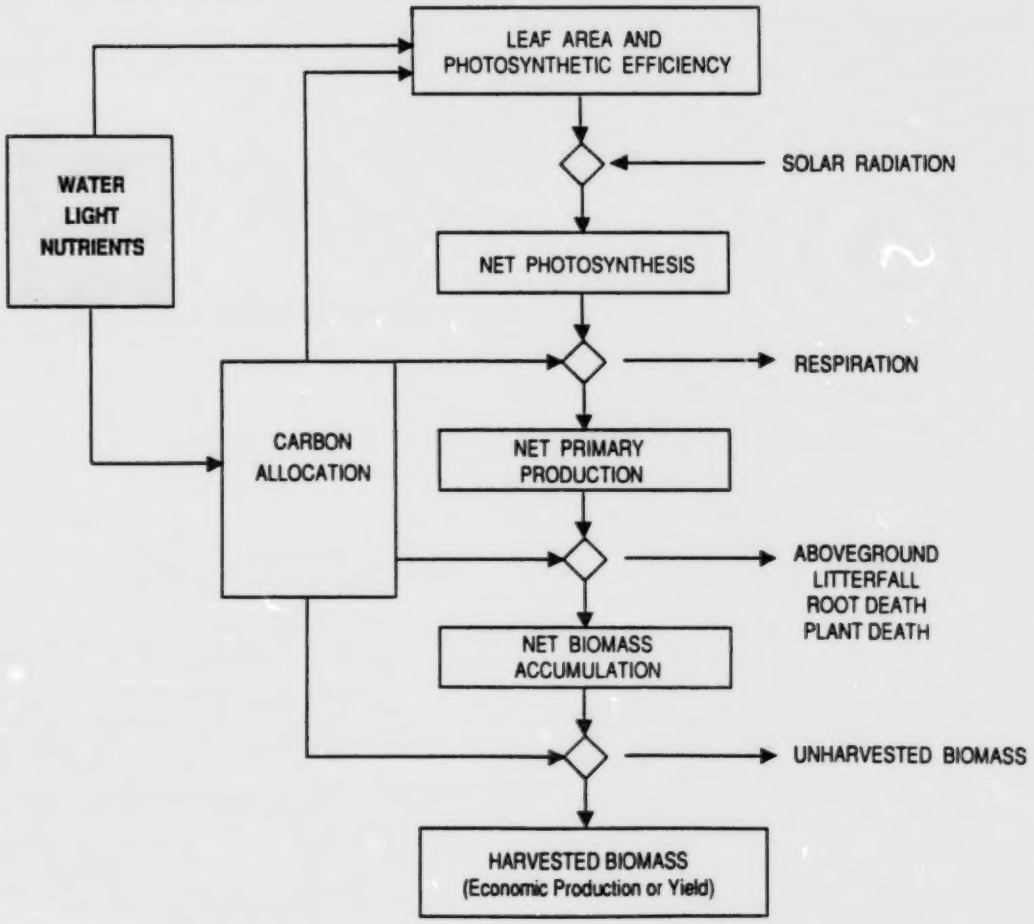
3 A seral stage is one of the stages which an ecosystem passes through after it has had its biotic community, microclimate and soil altered by natural or human-induced disturbance during its recovery back to its pre-disturbance condition. A seral stage is characterized by a particular plant community, animal and microbial community, soil condition, and microclimate. It is generally recognized by its characteristic vegetation.

---

4 The soil is not just the stuff that sticks to your boots. It is a living ecosystem in its own right. It has the roots of plants, animals, microbes, dead organic matter, a microclimate, water, a structure (an internal architecture), and functional processes. If one or more of these key components is missing or destroyed, the soil ecosystem may cease to function, or have its function diminished, as the supporter of plant life.

Figure 2.2

Factors that determine the capture of solar energy by a forest ecosystem and its eventual disposition in harvestable yield.



many centuries or even millennia, depending on the geology, climate, and various other characteristics of the site. Where the disturbance is much less severe (eg. removing only the dominant trees), the species composition of the recovering ecosystems will soon approximate that of the climax forest. Within a few decades, or as much as one or two centuries, the differences between the pre and post-disturbance ecosystem condition may be negligible. Where the disturbance is at the scale of individual tree death, minor changes will occur in the canopy gap so formed, but these will soon disappear if the surrounding trees close the gap within a few years.

Where a climax ecosystem is disturbed (eg. by clearcut harvesting) and subsequently redisturbed prior to its full recovery back to the climax condition, the landscape may be held in an intermediate seral condition for as long as this disturbance/recovery cycle is maintained. If the repeated disturbance keeps on occurring before the ecosystem has recovered to the condition prior to the preceding disturbance, the ecosystem condition may be pushed slowly but steadily back toward an ever-earlier seral condition (Figure 2.3).

In very wet forest ecosystems with deep, organic soil, or on dry, rocky ridge-top sites with thin, infertile soils, the greatest leaf biomass, and therefore the greatest ecosystem productivity, is generally associated with late seral or climax forests (Figure 2.4). In such forests, harvest-related disturbance to the soil should be minimized if forest productivity is a concern. On intermediate sites, especially those that have moist, fertile soils, forest productivity may not change dramatically over several seral stages, or may be highest in earlier or intermediate stages of succession where fast-growing deciduous hardwood or seral coniferous tree species grow. On such intermediate sites, harvesting and post-harvest site treatment may be done in a way that deliberately disturbs the ecosystem (eg. clearcutting and slashburning, or clearcutting and scarification) in order to create mid-seral ecosystem conditions that promote the growth and productivity of these species.

In concluding this discussion of successional change, we need to understand the components of a seral stage if we are to understand successional recovery. Each seral stage is merely a developmental stage of the same ecosystem; only the ecosystem condition changes. Each stage has a characteristic assemblage of plants, animals, microbes and a characteristic soil and microclimate. The microclimate is largely a function of the growth of the plants, which also determine the carrying capacity for the animals. In the absence of climate change, succession is therefore mainly a result of the development of the plant community, which in turn is largely determined by the soil conditions. In defining a seral stage of a particular ecosystem within a particular climatic area, the most basic parameters that must be described are thus the plant community and soil condition.

Figure 2.3

Diagrammatic representation of the successional consequences of different levels of disturbance during harvesting of the penultimate successional stage of three different types of sere in coastal British Columbia. Arrow 1 represents minimal disturbance which permits succession to proceed to climax over the subsequent 100 years. Arrow 2 represents the degree of disturbance necessary with a 100 year frequency to maintain the penultimate successional stage in perpetuity. Arrows 3 and 4 represent increasing levels of disturbance. The variation in the successional consequences of heavy disturbance between the three seres can readily be seen. (A) In the xeric environment, successional changes accompanying disturbance include loss of nutrients and of nutrient and moisture storage capacity. Recovery from excessive disturbance is slow and cannot readily be accelerated. Patterns of recovery are predictable. (B) In the mesic-hygric environment, overall successional changes accompanying disturbance are modest and recovery is generally rapid. Recovery can fairly easily be accelerated when it is undesirably slow. Note that both the degree and pathway of successional recovery are variable and difficult to predict. (C) In the hygric environment, the major successional changes accompanying disturbance are increasing wetness and loss of soluble nutrients. Recovery tends to be slow but can be accelerated by such techniques as drainage. As with the xeric environment, the pattern is very predictable. (After Kimmins, 1972. Copyright Canadian Institute of Forestry. Used with permission.)

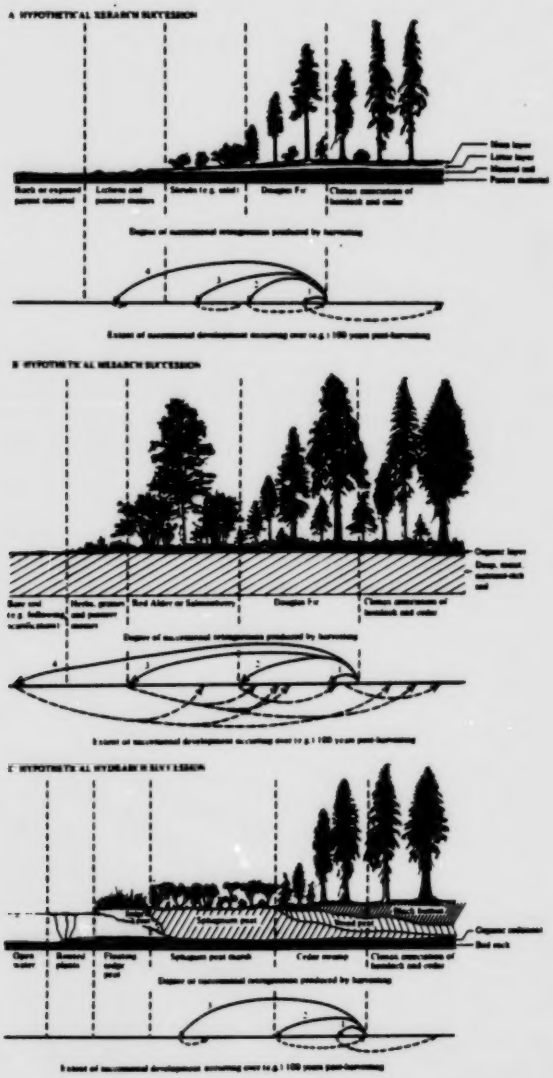
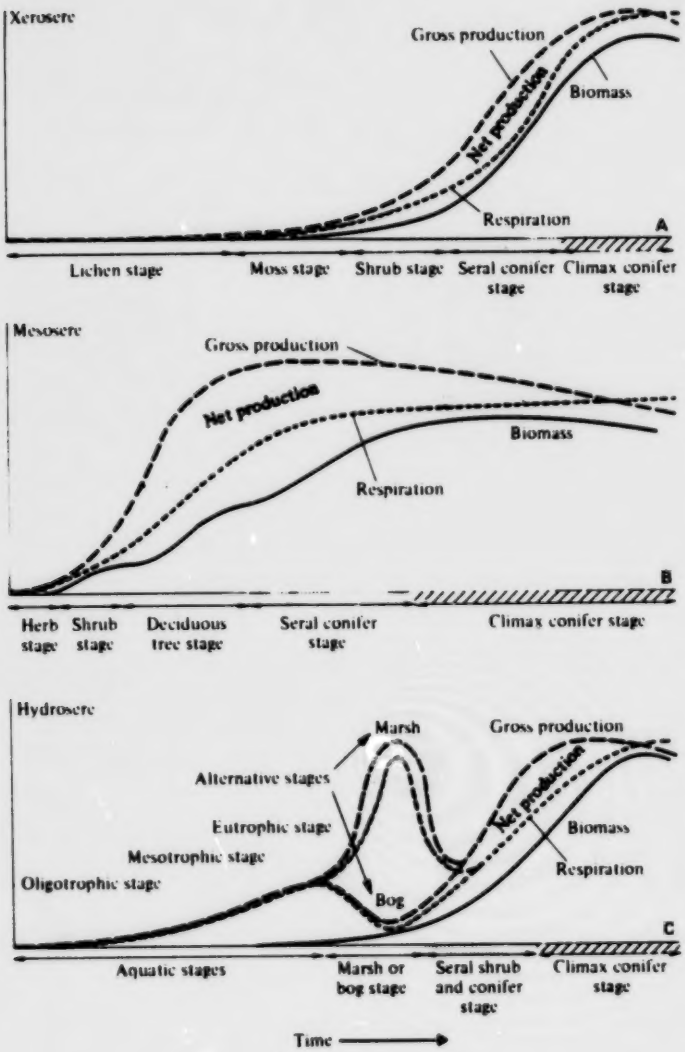


Figure 2.4

Variation in ecosystem productivity over the successional sequence on poor (dry), medium to good, and the excessively wet site types. The example is for low elevation forests on the southwestern B.C. Coast. From Kimmins (1987)



When climax forests are clearcut, an early seral microclimate is created. If the climax forest had a thick forest floor and this is not disturbed during the harvest, and if the clearcut site has a relatively hot, dry summer microclimate, few plants, including planted tree seedlings, may be able to grow for several years unless the forest floor is also disturbed to bring the soil condition into synchrony with the new microclimate. Most plant species are simply not adapted to grow on a site that has both an early seral microclimate and a late seral or climax soil condition (especially the depth and chemistry of the organic forest floor). Clearcut sites may also be much more subject to radiation frosts that kill seedlings if there is a thick organic forest floor. After a few years, natural decomposition of logging slash and the forest floor will resynchronize microclimate and soil conditions, but forest managers may choose to speed up the process by disturbing the soil mechanically or by the use of fire. Where such disturbance of the soil is undesirable, a forest microclimate that is appropriate for the undisturbed forest floor condition should be retained. The forest should either be managed under an uneven-aged system, or the clearcut opening should be limited to a size that provides the appropriate microclimatic conditions.

The need for site disturbance to resynchronize micro-climatic and surface soil conditions varies considerably from area to area. In very mild, humid climates, desirable tree species may be perfectly well adapted to the combination of open microclimates and climax forest floor conditions. No disturbance of the soil may be necessary in such circumstances. In areas with very cold mineral soils, areas where radiation frosts can damage seedling, or sites where there is a pronounced period of summer drought, some disturbance of the forest floor may be very beneficial, or even necessary. Obviously, each different situation must be assessed individually.

2.3 Other Aspects of Forest Ecosystems

The discussion above is limited to ecosystem function and temporal patterns of change, both of which are influenced by the structural components of the system. It is important that the ecosystem has an appropriate diversity of plants, animals, and microbes of the appropriate genetic characteristics and adaptations. This is necessary if the ecosystem is to function normally and recover predictably from disturbance under the prevailing site and regional climatic conditions. If the native trees are replaced by new species (or by different genotypes of the original species) that lack appropriate adaptations to the physical (climate, soil, fire) and biotic conditions of the site, ecosystem function can be expected to change, probably for the worse. Replacement of the native species/genotypes by well-adapted new species/genotypes does not threaten the future functioning of the ecosystem, however.

Loss of critical ecosystem components can sometimes have a very

negative impact on ecosystem function. Having said this, it should be noted that there are numerous examples from around the world of the successful establishment of non-native forests, either in areas of native forest that have been cleared, or in areas that were deforested centuries ago. These "human-made" forests lack many of the structural components of the original native forest, but have proven to be both productive and ecologically stable when established and managed in an ecologically-sound manner. The difficulty is in deciding which presently-existing components of a particular ecosystem are vital for its normal functioning, and which are important in its present seral condition, but are non-vital and perhaps not even necessary if the ecosystem is to be managed in a different seral condition.

Sometimes the negative effects of losing certain ecosystem components may not show up in the first rotation, but may result in declining productivity in subsequent rotations. Considerable caution is therefore required in making assumptions about the role of specific ecosystem components in the long-term-maintenance of ecosystem productivity. However, it cannot be assumed a priori that every living organism and every non-living object or condition in a particular seral stage of an ecosystem is equally important and vital for the future functioning of that ecosystem in the same or some other seral stage. A careful site-specific analysis is required, and conclusions reached in one type of ecosystem will not necessarily be applicable in ecologically-different types of forest.

2.4 Stratification of the Ecological Variability of B.C.'s Forests

British Columbia is one of the most ecologically-diverse landscapes of comparable size anywhere in the world. Indeed, it includes greater ecological diversity than many areas that are many times larger. More than two thirds and perhaps as much as three quarters of all the ecological diversity in Canada is represented in B.C. This makes forestry in B.C. much more complex than in competitor forest countries such as New Zealand, Sweden, or the south-eastern U.S.A. The landscapes of British Columbia include representatives of many of the major world types of ecosystem. Four out of the five major types of world climate are represented in the province, with a corresponding diversity of vegetation that varies from arctic and alpine tundra to broad-leaved evergreen and deciduous semi-Mediterranean vegetation, and from semi-arid/semi-desert grasslands to temperate rainforest. Within each of the major climatic belts there are climatic variations great enough to result in significant ecological variation. These are called biogeoclimatic zones (see the biogeoclimate zone map in Appendix 1). Within each of these fairly homogeneous climatic sub-units there are further subdivisions called biogeoclimatic subzones, each of which has its own unique range of ecological characteristics.

Each subzone is in turn a mosaic of ecosystem-types[5]. Topographic variation within the climatically-uniform subzone results in local variations in soil moisture and nutrient availability (ie. site biogeochemistry). From the dry, nutrient-poor ridge tops of small hills down to the moist bottom of a small valley (all with the same subzone climate), there are sequences of forest ecosystem types (or "site types") that are distinctly different from each other in structure, species composition, and function, and in their sensitivity to and recovery from disturbance (Figure 2.5).

Forest management in British Columbia must, by law, be practiced on the basis of the biogeoclimatic classification and site interpretation system developed by Professor V.J. Krajina and the B.C. Ministry of Forests. This world-class ecological stratification of B.C.'s forests provides an ecological foundation for the practice of environmentally-sound, sustainable forest management. The need now is to develop ecologically-sound guidelines for the management of each of the ecosystem-types in this classification, and to ensure that forest practice does indeed follow these guidelines. Preliminary guidelines have been, or are currently being prepared, and the current mechanism to ensure that these are applied is the Pre-harvest Silvicultural Prescription (discussed later).

2.5 Variations in Biological Diversity Following Disturbance

One of the global environmental issues that has fired the imagination of the public is concern about the global loss of biological diversity, especially that caused by deforestation in the tropics. The products of millions of years of evolution are being threatened by forest clearance in the tropics for agriculture, mining and hydroelectric schemes. There is considerable evidence in support of this concern, and the prospect that large areas of forest which can have more than 400 different tree species per hectare may be replaced by single species agricultural crops or by monoculture conifers (eg. tropical pines), eucalypts, or other tree crops has helped to fuel the international environmental movement.

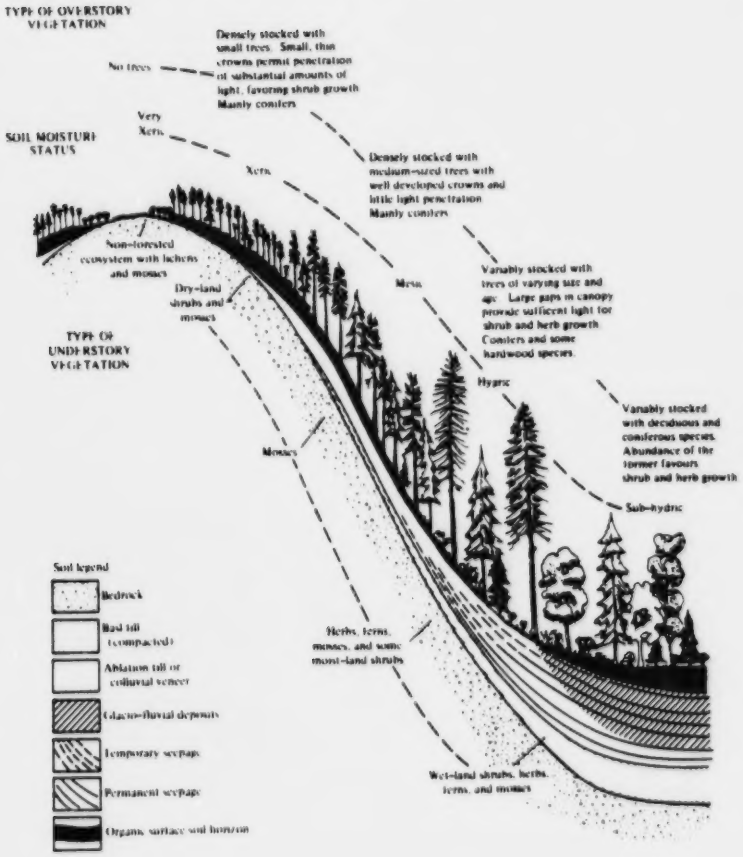
Uncritical comparisons are frequently made between deforestation in the tropics and timber harvesting in B.C. The global concern about the biological simplification of tropical ecosystems is being refocused on the forests of our province, and recent statements in the media have suggested that the diversity of our "temperate rain forests" approaches that of tropical rain forests. It is

---

5 The term ecosystem is a general term which refers to a natural system that has structure (living organism, a climate, and a non-living substrate), function (energy-flow, nutrient cycling), complexity, interdependency of its subcomponents, and which changes over time. The term ecosystem type refers to a specific type of ecosystem that is relatively homogeneous in its components, has a characteristic series of seral stages following disturbance, and a characteristic climax vegetation, soils, animal and microbial life.

Figure 2.5

Variation in ecosystems along a minor topographic sequence within a biogeoclimatic subzone. From Kimmins (1987).


TYPE OF OVERSTORY VEGETATION
No trees
Densely stocked with small trees. Small, thin crowns permit penetration of substantial amounts of light, favoring shrub growth Mainly conifers
SOIL MOISTURE STATUS
Very Xeric
Xeric
Densely stocked with medium-sized trees with well developed crowns and little light penetration Mainly conifers
Non-forested ecosystem with lichens and mosses
Dry-land shrubs and mosses
Mesic
Variably stocked with trees of varying size and age. Large gaps in canopy provide sufficient light for shrub and herb growth Conifers and some hardwood species
TYPE OF UNDERSTORY VEGETATION
Hydric
Variably stocked with deciduous and coniferous species. Abundance of the former favours shrub and herb growth
Mosses
Sub-hydric
Soil legend
Bedrock
Ablation till or colluvial veneer
Temporary seepage
Permanent seepage
Herbs, ferns, mosses, and some moist-land shrubs
Wet-land shrubs, herbs, ferns, and mosses

necessary, therefore, to enquire about how diversity varies naturally in the forests of B.C., and how diversity responds to disturbance and successional recovery. There are five major categories of biological diversity: 1. genetic variability within a given species, largely in response to geographical variations in physical and chemical environments (genetic diversity); 2. the number of species in a given forest stand or ecosystem (alpha species diversity); 3. variation in species composition between the different forest stands or ecosystems in a region (eg. a large valley: this is called beta species diversity); 4. variation in species composition between different seral stages of a particular ecosystem type (temporal diversity); and 5. variation in species along major elevational, latitudinal, or longitudinal gradients (ecoclinal diversity or geographical diversity). These measures of species diversity can also be applied to stand structural diversity and to the variation in productivity (functional diversity).

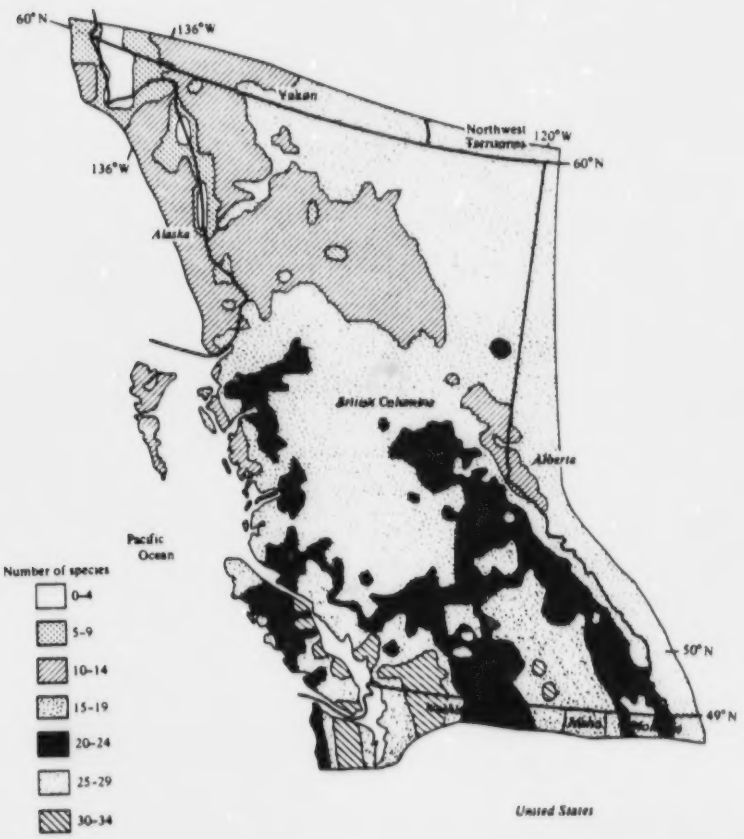
All these measures of biological diversity are subject to modification by natural disturbance (fire, insects, diseases, wind, etc.) and by forest management. However, they also reflect an underlying diversity of soils, topography and climate that is far less susceptible to change. The persistence of this environmental diversity guarantees the redevelopment of many aspects of biotic diversity following some disturbance of the biotic community.

Figure 2.6 shows the variation in regional tree species diversity in unmanaged forests across B.C. (ecoclinal or geographic diversity: not the diversity in individual forest stands). Diversity varies greatly, from a high of thirty to thirty-four tree species in the topographically and climatically diverse area of transition from coastal to interior climates in southwestern B.C., to as few as zero to four in very cold, glacier-dominated mountains of northwestern B.C. The alpha diversity of tree species is much less, of course, ranging from as low as one to a high of about ten in some parts of southern B.C. The general decline in both alpha and ecoclinal tree species diversity with increasing latitude is a phenomenon that is well documented for a wide variety of other organisms, leading to the general conclusion that individual local forests in B.C. are much less diverse than individual local tropical forests. There is a high diversity of forest types and forest ecosystem-types in the province, but most of these have relatively low values for most aspects of diversity; we have a high diversity of relatively low diversity forests.

Very old forests characteristically have high structural diversity (trees of many sizes and ages) and may have either high (tropical forests) or relatively low (northern forests) plant species alpha diversity. The alpha diversity of plant species in such forests is generally increased by disturbance because the ecosystem still supports many of the species that were present in the original plant community as well as many "weed" or "invader" species that

Figure 2.6

Tree species diversity in British Columbia. The highest diversity occurs in the area of climatic transition from coastal to interior climatic conditions. The area is mountainous and there is a high diversity of physical environments based on variation in elevation, aspect, and location within the transition area. (After Krajina, Klinka, and Worrall, 1982. Used by permission of J.G. Worrall.)



are characteristic of early seral stages. However, disturbance generally causes a reduction in structural alpha diversity: most of the species are herbs or shrubs. As succession proceeds, shrubs often replace herbs, and pioneer conifers or deciduous hardwoods replace the shrubs. Such tree-dominated early seral communities often have only a single tree species (monocultures), and they are often dense, even-aged stands with little or no understory; they have a low species and structural diversity whether they are natural or established by foresters. As these low diversity stands mature, their canopies break up allowing invasion by other species and/or younger individuals of the same species, raising both species and structural diversity. If left without disturbance for very long periods, species diversity in many temperate and northern forests may decline again as the climax forest condition is reached and the ecosystem is dominated by just one or two very shade tolerant tree species. However, structural diversity may increase.

The above discussion focused on plant diversity. Because animals and microbes are habitat-dependant, their abundance and diversity will generally reflect the diversity of the vegetation: both the alpha diversity and the landscape diversity. The diversity of forest floor conditions, particularly the abundance and variation in size and degree of decomposition of decaying logs, is also important, especially for smaller animals (soil animals, small mammals, and some birds) and microbes. However, there is not always a linear relationship between animal diversity and plant species alpha diversity. Sometimes the diversity of animals in northern ecosystems reflects the time since glaciation as much as the diversity of the plant community (eg. the diversity of insects in the canopy of European oak forest). Because plant species diversity also varies as a function of time since glaciers left the area, it is sometimes difficult to separate the effects of plant diversity and time since glaciation.

The pattern of change over time in species and structural diversity is highly variable between different types of forest ecosystem within a biogeoclimatic zone, between different zones, and in response to different types, frequencies and intensities of disturbance. It is clearly difficult to develop useful generalizations about biological diversity that are accurate for more than one or two biogeoclimatic zones, and sometimes different ecosystem types within a single biogeoclimatic subzone may exhibit significantly different temporal patterns of species and structural diversity.

A recent article in the Vancouver Sun (page 1, April 16) suggested that "B.C.'s temperate rain forests ... are amongst the richest and most biologically diverse ecosystems in the world". This statement implies a diversity that approaches that of the tropical rainforests, and yet there appears to be little or no scientific evidence to support such a conclusion. Vascular plant, vertebrate and invertebrate animal alpha diversity is much lower in B.C.'s

climax "rainforests" than their tropical equivalent, and the concept of species diversity that works well for plants and animals cannot be applied equally to the soil microbial community. While it is certainly possible that there is a high microbial diversity in B.C.'s rainforests because of their abundance of dead organic matter, there is no available scientific data on the topic. Bryophyte (mosses and liverworts) diversity can also be quite high in these humid forests. However, there is little scientific basis for a claim of high alpha diversity in such forests relative to the most species-rich forests of the world. There is similarly little support for the idea of structural diversity being as great in B.C.'s rainforests as in their tropical equivalents. Perhaps this article was confusing the great diversity of ecosystem types in the province that is a consequence of the great diversity of climates, topography and soils, with the relatively low alpha diversity of most of B.C.'s forest. Within British Columbia, the humid old-growth coastal rain forests generally do not rank number one in most aspects of diversity.

The reason for discussing this newspaper report is to illustrate the frequently inaccurate public perception about diversity in B.C.'s forests, and its relationship to forest diversity in other parts of the world. Scientifically-unsupported parallels are often made between various other aspects of B.C.'s forests and forestry and their counterparts elsewhere. Caution is needed in interpreting the significance of such parallels for British Columbia unless it can be shown that ecological conditions are very similar in the areas being compared.

2.6 Successional Considerations in Forest Harvesting

Different plant and animal species are found in different seral stages of any particular ecosystem type. Similarly, different combinations of species are found in similar seral stages of different ecosystem types along the topographic sequence within a biogeoclimatic subzone (Figure 2.5). Different combinations are found in different subzones. Some rare species may be restricted to a single seral stage of a single site type within a single subzone. Most species can be found on more than one site type within a subzone, some species occur in several subzones, and some are found in many zones.

This variation in the "ecological amplitude" of plant, animal and microbial species (little is know about this aspect of soil microbiology) should be considered in all aspects of forest management, including tree harvesting. Each plant species has its own particular soil and climatic (including microclimatic) requirements and tolerances. Each species of animal has its own habitat requirements (largely, though not solely, a function of the plant community), and will therefore react uniquely to a given type and intensity of management-induced or natural disturbance. In considering the ecological constraints on harvesting method and

frequency, the manager must evaluate the anticipated successional retrogression that will be caused by the harvest-induced disturbance, compare the anticipated seral conditions that will be produced with the site and habitat requirements of the desired species of plants and animals, and consider the effects on soil organic matter and nutrient inventories. The rate at which the particular ecosystem in question will recover to its pre-harvest condition or some new desired condition must also be estimated. This involves the concept of "ecological rotations": the time taken for an ecosystem to recover from a specific disturbance regime. Once the ecological rotation has been estimated, site-specific combinations of rotation-length and level of harvest disturbance can be developed that will ensure the maintenance of desired seral conditions over the tree crop rotation (Figure 2.7), as long as the climate does not change. Different aspects of ecosystem condition will have different recovery times, and therefore the length of an ecological rotation will vary according to which ecosystem characteristics are being considered.

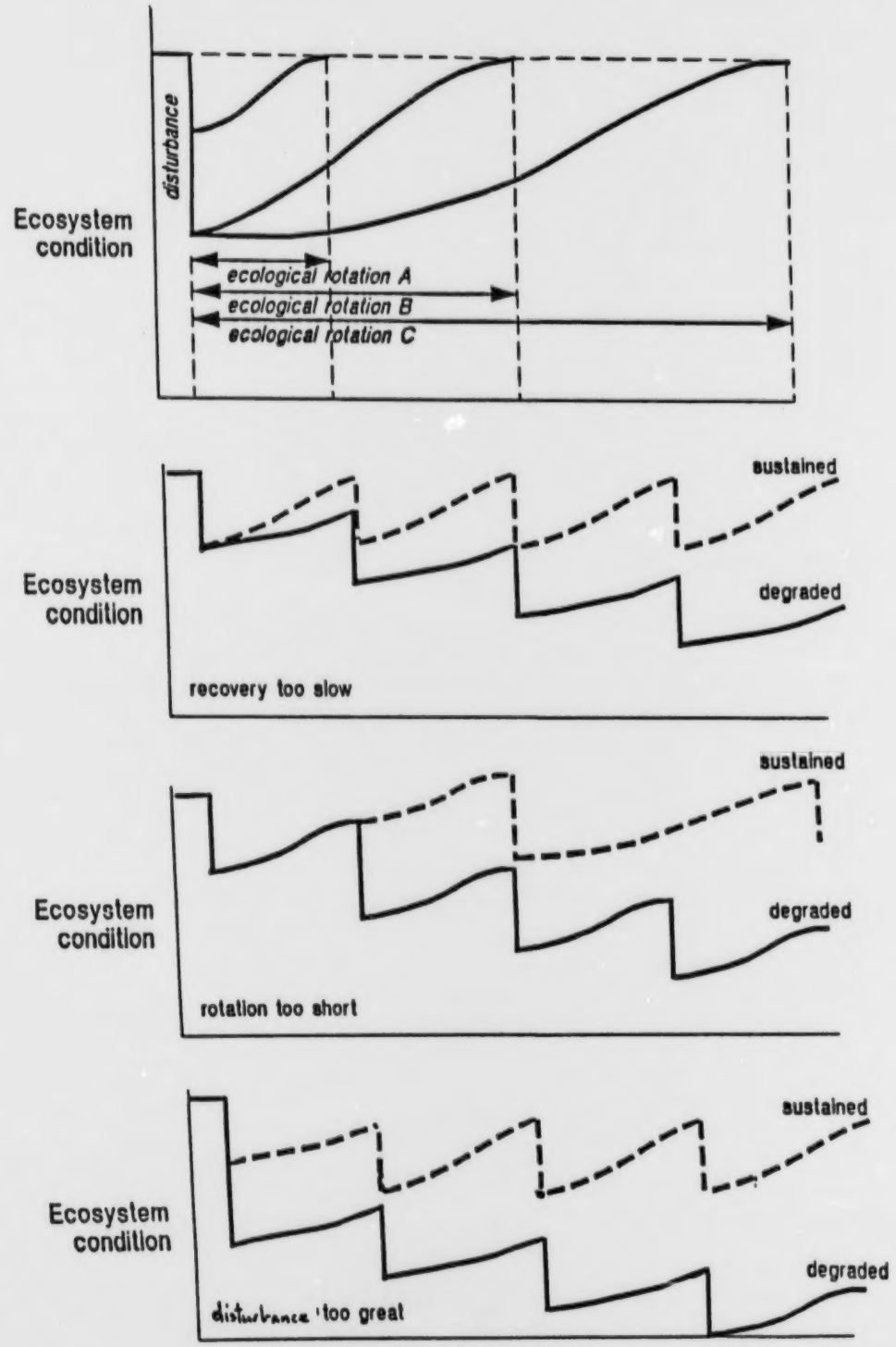
Estimation of ecological rotations is not easy. The best way is on the basis of experience, but in almost all cases we lack appropriate rotation-length field evidence about how long it takes for a particular seral stage of a particular ecosystem type to recover to its pre-disturbance condition following a particular type and intensity of disturbance. The growth and yield predictors and management planning tools currently in use in British Columbia are not appropriate for this purpose. They were not designed to be sensitive to questions of ecosystem disturbance and recovery. Ecosystem-management simulation models of the FORCYTE and FORECAST variety provide one way by which ecological rotations can be estimated for some aspects of ecosystem condition. These models are referred to in Appendix II.

2.7 Conclusions

Ecosystems are complex, dynamic, and functional systems. The biotic component is highly variable, both with time and from site to site. The non-living components, which determine the potential vegetation development of the ecosystem, are less variable over time, and less subject to management-induced or natural disturbance. Consequently, a similar type of plant community will always tend to develop in an ecosystem following disturbance or removal of the vegetation, unless the climate changes or there is massive alteration of the soil (relatively rare). However, it is the biotic components of the ecosystem that determine whether or not the environmentally-defined ecosystem potential is actually achieved. Understanding the ecological impact of timber harvesting thus requires an understanding of both the degree to which the physical and chemical conditions of the particular ecosystem have been altered, and the extent to which the biological mechanisms of vegetation and ecosystem recovery have been changed.

FIGURE 2.7

The concept of ecological rotation: the time to recover to the pre-disturbance ecosystem condition. The ecological rotation depends on the natural rate at which an ecosystem recovers from disturbance and the degree to which the ecosystem has been disturbed. Ecosystems will be degraded if recovery is too slow, the rotation is too short, or the disturbance is too great relative to one or more of the rotation length, the degree of disturbance, and the rate of recovery.



CHAPTER 3. A SHORT PRIMER ON FORESTRY

3.1 Introduction

There is considerable confusion in the minds of the B.C. public about forestry. As noted earlier, many people think that forestry is nothing more than clearcut logging, or that forest management is restricted to timber management. This confusion is understandable. In much of the province, clearcut logging and its aesthetic impacts are the most visible manifestation of forest management, and forestry in British Columbia has focused largely on the wood and wood fibre resource. However, forestry is, or should be if it is not, much more than just timber harvesting, and much broader than just timber management. Forestry is described as the "science, art and practice of managing forested landscapes for a sustained supply of a variety of goods and services". Forestry has always developed in a society when that society has perceived an actual shortage of some desired product(s) or value(s) from the forest, or the potential to develop shortages in the future.

The history of forestry reveals a strong tendency to evolve through a series of fairly predictable stages. This evolution has always started with the replacement of unregulated exploitation by a centralized, non-ecological, administrative approach, which has always been succeeded, sooner or later, by an ecologically-sensitive strategy for sustaining the biological diversity and productivity of the forest. This silviculturally and ecologically-sound phase of forestry tends to lead eventually to a socially as well as ecologically-sound strategy of forest land management in which aesthetics, non-timber values, and social considerations are given much greater emphasis. In British Columbia, we have passed through the earlier stages of this sequence. We were just entering the ecologically sensitive stage when the rapidly changing public attitudes towards forests resulted in enormous pressure to proceed directly to the final, more socially-responsive stage. A segment of the public has become incensed at the failure of the centralized, administrative, non-ecological, and aesthetically-insensitive approach to forest management that characterized much of the earlier days (and in some cases fairly recent days) in British Columbian forestry to sustain certain environmental values. These people have vehemently questioned why forestry in B.C. has not evolved to the subsequent stages more rapidly.

It is clearly time for the evolution of B.C. forestry to be accelerated into this final stage in which the aspirations of a broad cross-section of society are satisfied. This can only be achieved by a clear statement on the part of the land owner (the B.C. government, on behalf of the people of B.C.) as to what the public wants from its forests. This must be accompanied by the institution of a strategic planning process that will permit the tenant forest companies to satisfy the public's desires for these

values while at the same time remaining economically healthy and competitive in the international marketplace. However, in undertaking this evolutionary process, great care must be taken to ensure that actions taken to satisfy certain social criteria do not impair other social values provided by B.C.'s forests, that these actions are ecologically-sound, and that the forest management strategy that is adopted reflects the biological, environmental, ecological, social, and temporal diversity of B.C.'s forests.

Any evaluation of timber harvesting should be conducted within the framework of an understanding of: 1. the overall goals and strategies of forest land management; 2. the sequence of stand management practices which in aggregate constitute the rotation-length tree crop production system (the silvicultural system); 3. the relationship between stand-level silvicultural systems and regional timber management strategies; and 4. the relationship between stand-level and regional timber management and a variety of other forest-based resource values.

The evaluation of timber harvesting in British Columbia should be undertaken in the context of the present and past goals and strategies of management that have been set by the government of B.C., and administered, often with very inadequate resources to do the job, by the B.C. Ministry of Forests. The evaluation should examine both the practices and consequences of harvesting, and the institutional framework that has resulted in the type and rate of timber harvesting that has taken place in the province.

This chapter presents a "thumbnail sketch" of the overall nature of forest management as it should be, and as it hopefully will be, once B.C. forestry has entered the next phase in the evolution of forestry. No evaluation of the institutional framework for B.C. forestry is attempted.

3.2 The Objectives of Management and Their Achievement Through Management Planning

Forestry is a purposive, goal-oriented activity. Everything done by foresters should be a direct or indirect consequence of a clearly-stated set of land use and value production and/or protection objectives. These objectives are set by the land owner, but must also satisfy prevailing laws, statues and regulations pertaining to the management of land in the region.

In British Columbia, 95% of the land is publicly-owned. Therefore, the objectives of management are determined through the political process. Ultimately, the desired objectives of a (hopefully) well-informed B.C. public for the management of their forested lands are set through the ballot box and through the lobbying activities of public interest groups. The quality of forest land management we get depends on the resource-management philosophy of the government we elect, the pressure put on that government by the public to

implement this philosophy, and the commitment of the government to respond to this pressure. Proximally, the overall provincial objectives are set by the Ministry of Forests in order to satisfy the requirements of the Forest Act. Regional and local objectives are set by the managers responsible, in compliance with the Ministry's provincial objectives. The managers may be government, industrial, municipal, or private foresters or landowners.

Achievement of the objectives of management has traditionally been facilitated by preparing a management plan. There cannot be a single plan for an area the size of British Columbia, so the province is divided into a variety of management units. These management units are administered under several different types of forest land tenure, the details of which are not presented here. Not all management units in the province have a formalized forest management plan of the type described below, and there are presently a variety of institutional impediments that prevent the development and use of a "classical" management plan. However, I anticipate that planning documents of the type to be described will be required in British Columbia sometime in the future.

Many of the shortcomings in B.C. forestry today are thought to reflect the lack of adequate management planning mechanism in the past. This lack has been partly a result of the failure of policy and regulations set by the B.C. Ministry of Forests to achieve the level of planning that was needed to ensure good stewardship of the forests, and partly a consequence of the way various different forest-based natural resources are administered in the province. The failure to instruct students adequately on the preparation of management plans at the Faculty of Forestry, U.B.C. in the past has probably also contributed to the apparent lack of understanding of the importance of comprehensive, integrated management planning tools by many members of B.C.'s forestry profession today.

A forest management plan should have two parts. Part I consists of a description of the topographic, climatic, soil, hydrological, and biological characteristics of the management unit, and an inventory of all the physical, biological, aesthetic, social and other values provided by the forested landscapes in the unit. It should present a history of the area, insofar as this is known, to provide an understanding of the origins and causes of present conditions. Part I should end with a concise but complete statement of the objectives of management as defined by the landowner. Part II identifies the management strategy, the management techniques, the planning tools to be used to achieve these objectives, and the methods by which compliance with the objectives will be monitored.

Part I of the management plan identifies both the management opportunities and the constraints on management presented by the biophysical resources and characteristics of the area. It describes the tree-growth potential and the tree species best

suited to achieve this potential on each of a series of management sub-units of the landscape (compartments and subcompartments). The watershed, fish, wildlife, range, recreational and other values of these units are identified in terms of both the inherent values and the geographical location of the area relative to social demands for these values. Particular constraints on management are identified, such as unstable or sensitive soils, visually sensitive views, recreation and wildlife corridors, critical wildlife habitat and stream-protection riparian zones. The perceived risks of damage from insects, disease, wind and fire are identified. If actual or potential wilderness values are present in the area covered by the plan, these will also be described. In many cases, wilderness will be managed by an agency concerned with recreation, and the management plan for the area will be prepared by that agency.

Reflecting the statement of management objectives in Part I, Part II of the plan establishes the range of resource values that are to be managed for, the relative importance of the different values, and the actual and desired spatial and temporal availability of these resources. For each of the values so identified, there is a section that describes in general terms how the resource is to be managed over the longest time horizon being considered in the plan (this may essentially be "in perpetuity", or may be limited to the period of tenure of the tenant forest company), specific management strategies to be employed over some intermediate period (eg. the life of a tenure, such as fifteen to twenty years), and a detailed plan of management operations to be undertaken in the short term (one to five years). The plan identifies the geographical location of the activities for the next planning period and sets out criteria that define acceptable management standards (performance standards). Methods of record keeping are established, and a program of monitoring is described that will check that the actual management undertaken conforms to that which was planned. This monitoring program should include a method whereby the results of the monitoring are incorporated into the periodic revisions of the plan. Revisions of the short-term plans in Part II will be made annually, while the overall management strategy implied by the plan will be revised as needs arise, or on a cycle of perhaps five years. Ensuring conformity between the actual management and the established management plan is the responsibility of the landowner, which in British Columbia is the Ministry of Forests acting on behalf of the government and the public. Establishing the mechanism by which this is done is not normally part of the management plan.

This basic outline of the management plan does not imply a single, unvarying format for the planning document. For example, as technology has advanced, traditional maps have started to give way to computerized "Geographical Information Systems", and much of the information previously presented in Part I may now be embodied in such a system. There are many different possible formats, any one

of which may be suitable as long as the overall planning mechanisms as described above are provided.

The outline of the management plan given above implies a single planning document for all forest-based resources. The administration of natural resources in British Columbia disperses the planning and management of different forest-based resources amongst several different government agencies. Formal timber management plans are prepared by industry and the Ministry of Forests and are approved by these other agencies, rather than the more desirable situation of having the management plans for all resources centralized in one planning document.

3.3 Organization of Timber Management[6]

Forest management in British Columbia must be sensitive to the many public resources provided by our forested landscapes. However, timber production historically has been, and still is, the most important resource in terms of employment, the long-term stability of rural communities (the boom-and-bust image of B.C. forestry not withstanding), and the provision of raw materials, provincial revenues, export revenues, and a tax-base. Because of this dominant social and economic role, and because the organization and conduct of timber crop management has a major impact on other forest-based resource values, the basic principles of timber management should be understood if one wishes to understand the overall impact of forestry (including timber harvesting) on the landscape.

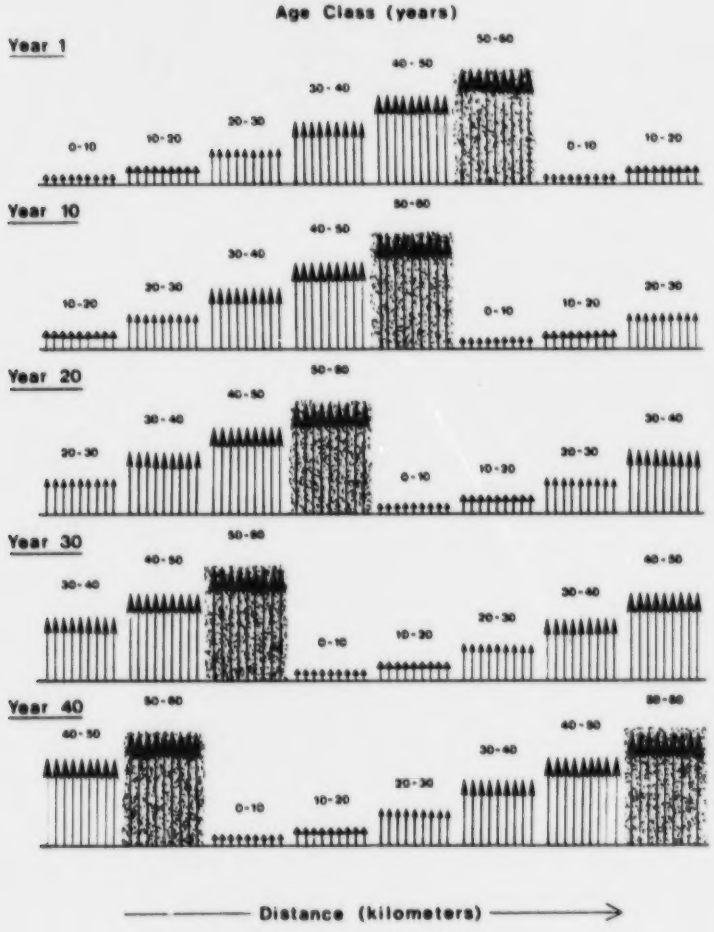
Where the objective of timber management is a reasonably constant annual production of timber, and where the silvicultural system involves "even-aged stand management" (defined below), forests must be organized so that they have a mosaic of stands covering all ages from the youngest plantations in recent clearcuts up to "mature" stands that are of a size, age and quality that renders them suitable for harvest. A forest which has such an "age class structure" is referred to as a "normal forest". In such a forest, a similar area and volume of timber can be harvested each year, and, in the absence of natural disasters or site degradation, this can be continued in perpetuity, the overall age class structure of the forest remaining constant (Figure 3.1). The concept of the "normal forest" can also be applied in uneven-aged forests. Such a forest will have an age-class distribution in its stands that ensures a reasonably constant annual or periodic harvest of timber without changing the overall long-term size- and age-class structure of the forest.

---

6 A integrated management plan for a forested landscape should contain sections dealing with all of the existing resource values. In the remaining parts of this chapter, only timber-management is dealt with because it is the harvest phase of timber management that is the overall focus of the paper.

FIGURE 3.1

Diagrammatic representation of the age-class structure of an even-aged "normal" forest. All age classes of forest are represented across the entire forest area at all times, but the geographical location of the different age classes varies with time. The stands that are ready for harvest (50-60 year old stands in this hypothetical example) are shaded. In an uneven-aged forest, all age classes would be represented over most of the area at all times, the annual harvest being distributed across the entire forest, rather than being concentrated in one relatively small area(the oldest age class of the even-age forest).



A forest in which there is only one area in each age class is said to have a single "working circle". In all but a very small forest, this will result in rather large patches of forest in each age class, and in the case of clearcut harvesting this will result in large clearcuts. In almost all cases, the annual cut for a managed forest is distributed between several or many smaller areas (ie. there are several working circles: Figure 3.2). The actual spatial distribution of the cut is determined by the objectives of management for a variety of forest-based resources, by the need for winter and summer logging areas, by the current market demands for species and wood quality, and by several other considerations. Forests managed under uneven-aged systems can also have a single or many working circles. The number of working circles will determine the number of areas to be harvested each year and their size.

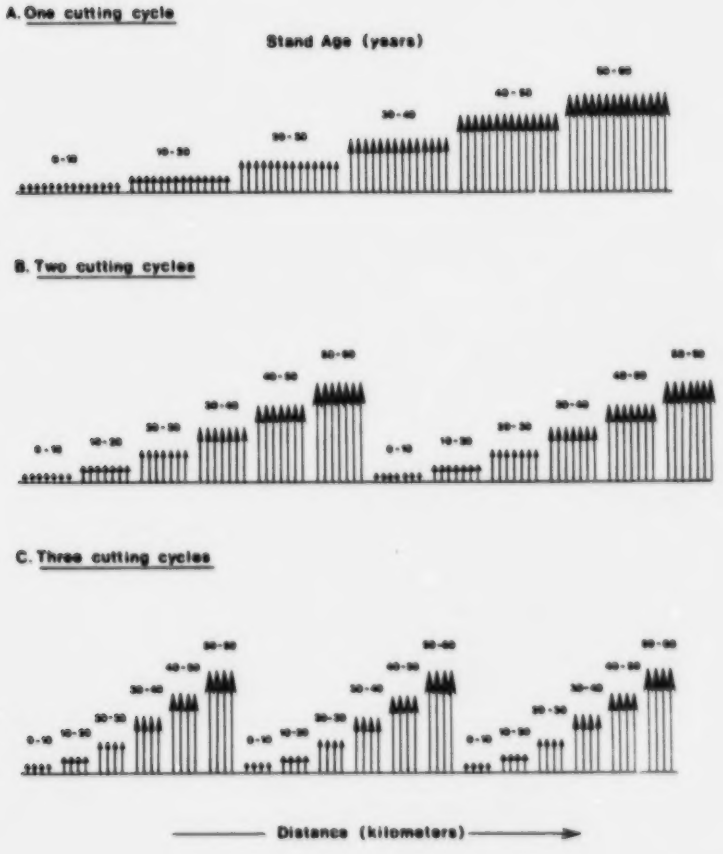
If the annual cut is distributed between several working circles, the harvest and subsequent silvicultural activities may be distributed geographically throughout the forest management unit. However, because of the high costs of road construction and maintenance, and because of the costs of travel time, clearcut harvesting in British Columbia in the past was often concentrated in a relatively small area, resulting in the "progressive clearcutting" of entire individual valleys or ridges over relatively short periods of time. This in turn resulted in large areas of rather uniform-aged second-growth stands, all of which will be ready for the subsequent silvicultural treatment at about the same time. This spatial concentration of harvesting and subsequent management activities has an obvious timber management advantage, and it has been argued by some silviculturists and ecologists that, overall, it may be less damaging to the environment than dispersed harvesting activities. However, such concentrated harvesting patterns have been widely criticised by the public because of real or perceived conflicts with other resource values. The Ministry of Forests introduced regulations for coastal logging (Coast Logging Guidelines) early in the 1970's to ensure the spatial dispersal of harvesting in all but special cases (eg. high windthrow danger areas, insect-killed areas). Similar guidelines are apparently being developed for the interior.

The tendency in British Columbia to have very large geographical areas in individual forest management units, and to have had relatively few working circles in these units in the past, resulted in a history of large portions of local areas being harvested over relatively short periods of time. This led to the "boom-and-bust" and "cut-and-run" image of forestry, even where the annual rate of cut over the entire management unit may have been sustainable.

The spatial distribution of the annual harvest has very important implications for wildlife, water, fish habitat, range and recreation. Many of the conflicts with these other resources have had as much to do with the spatial distribution of the harvest

Figure 3.2

Diagrammatic representation of the age-class structure in an even-aged forest with one (A), two (B) and three (C) cutting cycles. Clearly, the size of the area to be harvested in the oldest age class is much smaller where there are several cutting cycles than where there is a single cutting cycle. The greater the number of cutting cycles, the more closely the structure of the even-age forest approaches that of the uneven-aged forest.



as with the ecological and environmental impacts of any particular harvest operation. The frequent failure to allocate the cut in a spatial pattern that minimized conflicts with other resources reflects the lack of an adequate planning framework for forestry in the province. Without an appropriate management planning mechanism, timber management has lacked specific non-timber management objectives, and has lacked site-and situation-specific performance standards. The development of such objectives and standards must be "holistic" and employ a systems approach. It is so easy to create new problems if solutions to original problems are sought in a narrow, single-resource context. The best way to avoid this is to ensure that the management plan for an area is comprehensive and considers all relevant resource values.

3.4 Regional and Local Aspects of Sustained Timber Yield

Regional Sustained Yield[7]

The traditional concept of sustained yield in forest management has been the sustained flow of forest products (timber, wildlife, water, recreational opportunities, etc.) from a region, or from a specific forest management unit (eg. a Tree Farm Licence). Sustained yield of wood products requires, amongst other things, a "normal" age class structure. Where past fires, logging, insects or diseases have removed large areas of forest of a particular age (in even-aged forests), or certain age classes in uneven-aged forests, the future flow of forest products and the size of the related employment may fluctuate over time.

The area or volume of timber cut each year from a forest management unit (ie. the level of harvest) is referred to as the "annual allowable cut" (AAC). There are many factors to be considered in deciding on the level of harvest, and there are many different possible levels of harvest according to how the forest will be managed. There has been considerable debate over the relative merits of the different approaches used in choosing the level of harvest, and the assumptions that must be made in setting the AAC. In general, there has been a trend towards increasing flexibility in the level of harvest permitted, and away from the use of rigid formulae. In a managed forest with a normal age class structure, the AAC can be considered to be equal to the sum of the annual increment (the annual increase in harvestable volume or biomass) in all of the stands, and this should be equal to the volume in the oldest age class. In such forests, the AAC is sensitive to the

---

7 This discussion does not describe the current method of AAC determination in British Columbia which is complex and involves the use of computer models rather than simple formulae. Instead, the discussion merely explores some of the fundamental concepts that lie behind most AAC determinations. In British Columbia, there is an elaborate system by which the basic AAC estimate is factored downwards to reflect losses to fire, insects, diseases, other land uses and protection forests, and for reasons of environmental sensitivity, loss of site productivity, economic inaccessibility, and impacts on other resources.

quality of forest management practices. However, the age class structure of most B.C. forest management areas is not normal: most management areas have a very unbalanced age structure. As a result, the AAC has been more sensitive to the rate at which young stands will become ready for harvest than to the rate at which they are currently accumulating timber volume.

Where part of the management unit is old growth forest, the level of harvest may be closely related to the volume in the old growth stands divided by the number of years over which the supply of old growth will last(ie. until the second growth stands become ready for harvest). Levels of harvest in such forests thus appear to be more sensitive to the rate of logging of the old growth than to the effect of current management practices on site productivity in the second growth stands. However, the rate at which the old growth is logged is largely determined by the speed at which second growth stands become ready for harvest, which in the long-run is influenced by the speed of regeneration and rate of stand growth. Thus, in theory the AAC is influenced by the quality of stand management, even in old-growth-dominated forests.

According to the rate at which an unmanaged old growth forest is harvested, the age-class structure of the first rotation managed forest may be very different from that of the ideal "normal forest". Short term economic considerations often suggest that it is more profitable to ignore the policy goal of achieving a normal age class distribution in one rotation. However, harvesting levels in British Columbia are constrained by B.C. Ministry of Forest's policy to achieve a balanced age-class structure within one rotation and to have a long-term sustained yield. The historical patterns of old growth harvesting, together with regeneration failures, changes in utilization standards and species utilized, and natural disasters (fire, windthrow, insects) make the achievement of this provincial goal difficult. As a result, AAC's in British Columbia will tend to vary over time as harvest levels are adapted to allow for these factors.

The age-class distribution of a forest has important implications not only for the AAC and its viability over time; it also affects many other forest resource values. Variations over time in the area of forest in various different age classes will determine the availability of habitat for various wildlife species, will affect the recreation and range potential of the area, and may have significant implications for fish and water resources. The spatial distribution of the different age classes across the landscape may also be important.

Where maximization of economic returns from timber products is a major objective of management, the rate of harvest may be temporarily reduced to below the AAC when the price of timber is low, and increased to above the AAC when the price is high. Alternatively, a company may wish to increase the rate of harvest

temporarily to pay for investments in new mills, for new pollution-control equipment, or for silvicultural investments. Reflecting the important economic role of forestry in British Columbia, forest companies are allowed to vary their rate of cut by 50% in any one year, as long as they are within 10% of their AAC in any one five year period. This degree of flexibility carries with it a degree of risk for future age class structure and AAC, but seems reasonable as long as it is adhered to (the policy did not work well during the recession of the early 1980's when record volumes were harvested by many companies at a time of low timber prices in order for the companies to "stay alive" financially) and is conducted without unacceptable impacts on other resource values. An audit of harvest levels is conducted periodically by the B.C. Ministry of Forests to ensure a reasonably even supply of timber over time.

Sustaining Local Site Productivity

Harvest levels in British Columbia in the past have been determined by the age-class structure of the whole forest management unit, the rate of deterioration of timber in the remaining mature or old-growth forest, the rate at which the second growth forest became "operable" (ie. harvestable), and the rate at which forest area and volume was lost to natural disasters (fire, insects, wind, etc.). Where a management unit contained a significant area of old-growth, the volume of timber harvested in any year was relatively insensitive in the short term (a few years or decades) to any negative impacts of forest harvesting on site productivity, to regeneration failures, or to early stand treatments because of all these other factors. The rate of harvest has thus been determined much more by regional or whole-forest considerations than by local site considerations. However, if over a period of many decades there were to be a repeated failure to regenerate harvested areas adequately, or if there was a continuation of practices that lowered site productivity, there would be a reduction in forest biomass and growth, and a progressive reduction in AAC's. This would also contribute to fluctuations in future AAC's because of the perpetuation of forest age-class structure problems. Since adequate regeneration is now required by law, and since the success of regeneration has improved dramatically over the past decade, regeneration failure should not contribute to AAC fluctuations in the future. Reduction in site quality, if it occurs, will result in AAC reduction, but only if it is detected.

Sustained timber yield over one or two decades thus has more to do with the past history of forest harvesting, management and disturbance and with current policies of old growth harvesting than it does with the impact of current harvesting and management on site productivity. On the other hand, sustainable development of the timber resource over several rotations is closely related to the impact of management on soils, the management of ecological

succession, and anthropogenically-induced changes in regional climates (ie. global warming).

3.5 The Tree Crop Production Cycle: Silvicultural Systems

Forest harvesting is one component of the tree crop production cycle. The conduct of silvicultural activities throughout the cycle will affect both the engineering and economics of harvesting, and according to how it is done the harvesting method may dictate what silvicultural system must be used in the future. Clearly, there should be close coordination between harvesting and the other aspects of growing tree crops.

Tree crops can be grown under one of two major types of silvicultural system: even-aged and uneven-aged. In the former, there is a final harvest in which all or most of the older trees are removed and a relatively even-aged new tree crop is established. In the latter, individual large trees, or small groups of larger trees, are harvested periodically, leaving the smaller trees to continue growing. In terms of ecological succession, most even-aged management deliberately creates ecological disturbance to push the area back to an earlier seral stage that favours the growth of a mid-successional or early-successional crop tree species and associated birds and animals.

In contrast, the lower degree of environmental change caused by most uneven-aged management usually maintains later successional or climax site conditions that favour late successional tree species and associated wildlife. In even-aged management, sustained annual yield of timber products results from the management of a relatively large management unit (several thousand hectares). In uneven-aged management, in which all tree age classes are represented in a relatively small area, a small but sustained annual timber yield may be possible from stands of only a few tens of hectares in size.

Traditional uneven-aged management may be appropriate for climax tree species, for protection forests, in hot, dry climates, for some subalpine forests, for forests in which frost creates regeneration problems, or for areas where certain wildlife, watershed, recreation, soil, or other values require a permanent forest cover. Traditional even-aged management is generally more appropriate for early and mid-successional tree species, for forests with moderate climates or cold soils, for species of wildlife adapted to disturbed ecosystems, and in situations in which it is undesirable to have harvesting equipment entering the forest too frequently because of soil compaction, damage to tree roots, and the accompanying insect, disease and wood damage problems. Even-aged management can require very much less length of roading than uneven-aged management, especially in steep mountain topography, but this also depends on the type of harvesting equipment used.

Research in western Oregon has suggested the development and use of new silvicultural systems that do not fit neatly into the traditional even-aged vs. uneven-aged dichotomy. Retention of "wildlife green trees" and dead snags at the time of final harvest as suggested by this "new forestry" (actually, it is similar in some respects to old European two-storied high forest systems) creates a two age-class forest. If this were to be repeated at successive harvests, an uneven-aged forest would eventually be created, or the two age-class forest could be perpetuated.

A. Even-Aged Management

Following harvesting, the site is regenerated. Where natural regeneration is being used, careful removal of the tree crop can leave sufficient "advanced regeneration" of seedling and saplings that were already established in the understory of the previous stand to create a new crop. Advanced regeneration may occur naturally or may be encouraged by a late thinning or "regeneration cut" that stimulates regeneration by increasing light and reducing root competition. The acceptability of advanced regeneration will depend on the species, the spatial distribution of the regeneration, its vigour, and its ability to respond to release. In some types of forest, advanced regeneration is old, suppressed, and/or diseased and will not result in a healthy new crop of the desired species composition. Such advanced regeneration, where it has been kept, has resulted in degraded forests that are often referred to as a "green lie". Alternately, a scattering of "seed trees" may be left standing after removal of most of the crop; these are harvested after they have blown over or when adequate regeneration has occurred. Intermediate between these two strategies is the "shelterwood" system in which sufficient trees are left to modify the microclimate in the stand as well as to provide a seed source. Occasionally, scattered "leave-trees" may be left to grow for the duration of the next rotation to provide high-value large diameter logs. This "two-storied high forest"[8] strategy may be appropriate where there is a strong market for two sizes of logs, or where wildlife habitat considerations require the retention of some large trees. Where trees regenerate vegetatively by coppice sprouts from the stump or root suckers, this may be used as the method of regeneration.

Because of seed predation, weed competition, the unreliability of good seed years, and other factors that may cause the natural regeneration of desired tree crop species to fail, there has been an increasing dependence on the planting of nursery-grown seedlings. The desire to change tree species or to establish

---

8 "Two-storied high forest" is a technical term referring to a silvicultural system that produces a forest with two distinct age classes and canopy layers of trees. The name tells you nothing about the actual height of the two canopy layers.

"genetically-improved" seedlings of the same species, and the use of harvesting methods that mitigate against natural regeneration (very large clearcuts, or methods that produce microclimates or surface soil conditions that are unsuitable for natural seedling establishment) have been further reasons for planting. Much of the recent planting has been to reforest "not satisfactorily restocked" (NSR) areas where plantations or natural regeneration failed in the past.

For both natural regeneration and planting, some site preparation may be desirable or even essential. Site preparation to promote regenerating may be done in either even-aged or uneven-aged forests, but it is most commonly done in even-aged forestry following clearcutting. Slashburning can improve access for planting and temporarily reduce weed competition (thereby reducing the need for herbicides, although it may increase the abundance of some weed species), but it can result in an undesirable loss in soil organic matter and nutrients if not applied in an ecologically sensitive, site-specific manner. Mechanical site preparation can achieve the same results and improve soil structure, although it can also cause soil compaction on some sites and can result in serious losses of organic matter, nutrients and top soil if done incorrectly (eg. many cases of windrowing). Herbicides can control weed problems with minimal adverse impacts to the soil, but may do little to improve access for planting or future silvicultural activities or for wildlife, on sites that have large quantities of logging slash.

The need for site preparation depends on the type of forest (climate, soil, species composition), the condition of the forest prior to harvesting, the degree of disturbance to the soil, to logging slash and to minor vegetation during the harvest, and the access requirements of planned future silvicultural activities and for wildlife. In many cases, prompt regrowth of the forest will require some type of site preparation. The need for site preparation is usually much greater following the logging of mature or old-growth forest than following the harvest of second growth forest.

Following planting, weed control may be necessary until the trees are "free to grow". This may simply be when they are taller than the non-crop vegetation, or may not be until they have achieved a closed canopy and shaded out the understory. The latter reflects the fact that competition between crop and non-crop plants may be more intense below-ground than above-ground. Although the use of herbicides is unpopular with the public, is expensive, and water quality considerations may limit their use on the very sites on which they may be most needed (moist, fertile valley bottom sites), herbicides often constitute the least environmentally disturbing but effective weed control method. (This comment assumes responsible use of the appropriate herbicide.) Hand weeding is probably similar to herbicides in its degree of site disturbance,

but is often not very effective (it may have to be repeated annually or more than once a year for several years) and can be very expensive. Mechanical control of weeds can be effective but can damage some types of soil. Biological weed control (eg. sheep or cattle) can be very effective in some cases if the animals are carefully managed.

Once the new tree crop is well established, it should be "spaced"[9]. This reduction in number of trees per hectare promotes continued rapid and even stem-growth of the remaining trees, removes damaged, diseased and deformed trees, permits alterations of the tree species composition of the stand, and prolongs the availability of browse for certain species of wildlife. Wide spacing leads to trees with longer crowns and larger branches, which can reduce timber quality unless lower branches are pruned off. Heavy branching can also occur in stands of moderate density but where the trees are not evenly spaced. Early spacing is especially important for naturally regenerated crops which are often overstocked and have a rather uneven distribution of trees (alternating dense clumps of trees, and sparse areas). The number of trees that constitute "adequate stocking" varies greatly as a function of stand age, ecosystem type, and species (eg. 400 trees per hectare in a young ponderosa pine forest vs 1500 - 1800 trees per hectare in a young lodgepole pine forest in the southern interior).

As the tree crop grows and closes canopy after spacing, it enters the phase of maximum nutrient uptake demand from the soil, and fertilizers may be required to maintain growth or to correct nutrient deficiencies. If rapidly-growing non-crop tree species are able to invade the stand following the spacing and overtop the crop trees prior to canopy-closure, manual cutting or herbicide treatments may be needed to release the crop trees from this competition.

As the stand continues to grow, the smaller trees will be shaded and will eventually die. The competition involved in this "stand self-thinning" can result in periodic fluctuations in stem diameter growth of the remaining trees, with attendant timber quality problems. The forester can prevent this, and obtain an intermediate harvest, by doing a commercial thinning. Where this is done near the end of the rotation, it may be designed to stimulate advance regeneration in the understory in preparation for the next crop. Commercial thinning results in a reduction of input of dead tree stems to the forest floor. Concerns have been

---

9 Since the establishment of Bill 70 in 1987, the amount of juvenile spacing that has been carried out in young stands in British Columbia has been significantly reduced. The removal of incentives, such as Section 88, and the lack of assurance that the improved growth will be recovered by the licensee has greatly reduced the investment by industry in this important silvicultural practice.

expressed by some ecologists about this. European and Scandinavian forests have grown for centuries without such woody inputs to the forest floor, but the progressive loss of rotting wood from some of B.C.'s forests if they are commercially thinned may certainly have some effects on their long-term productivity. This is an issue that can be explored to some extent by the use of ecosystem management simulation models.

The final clearcut harvest removes the present crop and prepares the site for regeneration. In the case of natural regeneration, the harvest may be designed specifically to enhance the establishment of natural seedlings. The manner in which the harvest is done plays an important role in early stand silviculture. Excessive slash, soil compaction or erosion can lead to regeneration difficulties and the need for sometimes costly and sometimes damaging site preparation methods. All final harvesting should be closely integrated with the subsequent regeneration activities to avoid site damage, regeneration failure, and costly site preparation. This is achieved by the requirement stipulated in the Forestry Act for a Pre-harvest Silvicultural Prescription (PSHP). This document must be completed for every area that is to be harvested. It includes a recommendation about the type of logging equipment that is to be used and the type of equipment that should not be used, the type of site preparation treatments that are to be applied, and the method of reforestation, including natural regeneration or planting, the species and type of seedling for planting, and the spacing and stand maintenance activities that should be undertaken.

B. **Uneven-Aged Management**

Uneven-aged management attempts to maintain the full range of desired tree age classes over relatively small areas (a few hectares). Even-aged stands can be converted to uneven-aged stands by creating small canopy openings to stimulate small patches of natural regeneration at various times throughout the rotation. Obviously this is a slow, drawn-out process. More often, uneven-aged management is applied to stands that already have a range of tree age and size classes.

Uneven-aged management may involve one of several different silvicultural systems: 1. individual tree selection in which individual large trees are harvested and smaller trees are cut in a manner than maintains a desired age and size-class distribution and structure in the stand; 2. small group selection, in which small groups of trees that are similar in size and age are removed at one time, creating a small area of even-aged regeneration. The resulting small group of trees is periodically spaced and/or thinned as if it was an even-aged stand. In this case the mixed-age character of the stand is provided by a mosaic of small patches within which the trees are essentially even-aged. Obviously, group selection requires a larger area for a full representation of all

age classes than does single tree selection; 3. Multi-storied systems in which the forest may have two or more distinct crown levels representing two or more age classes of trees, rather than a mixture (single tree or small group) of all age classes. The lower canopy trees remain when the uppermost canopy trees are removed. Such multi-storied, mixed-aged systems grade into the two storied high forest mentioned under even-aged management. The latter differs from the former in the extent of the uppermost canopy layer. This is the type of system envisaged in the new silvicultural systems that are being tested in Oregon and some other parts of western U.S.

Uneven-aged management offers a variety of benefits in comparison to even-aged management. It is more aesthetically pleasing to many people. Wildlife habitat conditions remain fairly stable over time, benefiting species of animals that are favoured by continuous cover of multi-storied forest and especially those species that depend on "old-growth" characteristics of the forest. It is a good system for very small forest units because a continuous though small supply of logs can be harvested from a relatively small area of forest that would yield an intermittent supply if managed under an even-aged system. Savings on planting costs and site preparation costs may offset additional harvesting costs that are incurred. Where the regulation of snow melt is important, group selection (or small patch cutting) may have an advantage over larger clearcuts. Natural regeneration of shade-tolerant or shade-requiring species may be easier under uneven-aged than under even-aged systems, depending on climate, soil conditions, and other site factors. Various aspects of biological diversity are less varying over time in uneven-aged stands than in uneven-aged stands. It is less clear as to whether overall landscape diversity will be greater or less with uneven-aged than even-aged management. This will probably depend on the type of forest and how the two different systems are implemented.

Against these advantages, there are a variety of disadvantages. The frequent movement of harvesting equipment into the stand can result in damage to the roots and stems of the remaining trees, leading to root rots, increased susceptibility to windthrow, and stem decay. Decay fungi can enter the remaining trees by invading cut stumps, travelling down into the dead roots, and crossing into live roots where these are closely associated with the roots of the cut tree. Similar invasions of pathogens into scars or bruises on stems and roots of live trees can spread to other, undamaged trees. Physical soil damage can be done if there is frequent passage of equipment, leading to soil compaction on fine-textured materials, and gully erosion on steeper slopes. The density of roads may be increased, and on very steep hillsides that would be cable logged in an even-aged system, roads may occupy a very substantial proportion of the site. The lower volume of logs removed at each harvest will generally increase the cost of harvest per m^3. If uneven-aged silviculture is attempted on moist, fertile sites, the

canopy-opening caused by partial harvesting can stimulate severe competition from non-crop vegetation, and this may be much harder to control than in a clearcut. This can result in difficulties in obtaining natural regeneration. Very careful manipulation of the canopy is required to avoid this problem, and this may increase costs of management.

Not all these advantages or disadvantages (and others not listed here) will occur in any particular forest ecosystem. In some types of forest the advantages will outweigh the disadvantages, and uneven-aged management will be indicated. In others, even-aged management will be the system of choice. In the majority of managed timber-production forests in British Columbia, silvicultural considerations on their own will lead to the choice of even-aged management. As has been the experience in Sweden, selection harvesting in uneven-aged forests at cold northern latitudes does not result in healthy, productive forest ecosystems. The degraded forest that results is not very good habitat for many species of wildlife.

3.6 Conclusion

Timber harvesting is an integral part of timber management, which in turn is an integral part of forest land management where timber production is one of the objectives of management. It is visually one of the most dramatic silvicultural practices and has the potential to produce significant and prolonged alterations in ecosystem structure and function. These alternations may be either desirable or undesirable, depending on the objective of management, the type of ecosystem, and the degree of ecological alteration produced. Forest harvesting should not be judged solely in terms of short term site impacts, but in terms of overall rotation length management objectives.

Experience around the world has repeatedly led to the conclusion that in order for silviculture to be successful, the harvesting and silvicultural system used must be ecologically-sound. Experience with uneven-aged management and selection logging the cold northern spruce-pine forests in Sweden in the first half of this century led to what has been called the "green delusion": areas of relatively aesthetically-pleasing forest growing much more slowly than even-aged forests established by clearcutting. Forest management must reflect the physical and chemical condition of the particular site, the ecological requirements of the forest plants that are to be grown, and the habitat requirements of a broad spectrum of animal and microbial species. The harvesting and silvicultural system used in B.C. is now required by law to be decided prior to harvesting decisions on the basis of an ecologically-based pre-harvest site assessment. This should lead to a reduction in the number of conflicts caused by timber harvesting in the future.

CHAPTER 4. TECHNICAL CONSIDERATIONS IN THE SELECTION OF THE METHOD OF TIMBER HARVESTING

The tree growth potential of a site is determined by the climate, soil, topography and living organisms (plants, animals and microbes). However, the degree to which this ecological potential is converted into an economic timber crop depends on a variety of social, economic and management factors. Similarly, while the success of silviculture in producing a tree crop determines the potential yield of timber products and economic value, a variety of other factors determine how much of this potential is actually realized. Several of these factors, or the effects they have on silviculture, contribute to the selection of the method of forest harvesting.

4.1 The Role of Markets and Product Values in Determining Silviculture

Trees may be grown for a wide variety of reasons. Where they are grown as an economic timber crop, their value is not determined solely by their size and rate of growth. It is also determined by the anticipated value of their wood and availability of markets.

There is little point in growing a tree solely for its economic value if you cannot sell it after you harvest it for enough money to cover its cost of production. The demands of the market have always had a strong influence on the way commercial timber crops have been managed. Foresters grow stands of the species, size and quality that they believe will be in greatest demand and/or will command the highest price when they are harvested. In very short-rotation tree crops, this merely requires a flexible response to the short-term demand and supply situation. In long rotation crops, a great deal of guess work is involved. What will people be using wood for in the eighty to one hundred years it takes for a tree crop to mature in central and northern British Columbia? Because of the great uncertainties in answering this question, some people believe that one should simply grow the species that are most productive on the site in question; technology will find a way of using it (them) when the trees are ready for harvest. Others believe that they can predict the trends of the future, and they will recommend a species (or species mixture) and a silvicultural system that they think will yield the highest future value. It is certainly possible to predict declining future supplies of certain valued species or wood types, and it seems sensible to grow these. However, uncertainty about future markets remains as one of the many risk factors in silviculture.

In addition to determining the species to be grown, markets and economic conditions determine the rotation length and the proportion of the tree biomass that can be utilized. Markets and variation in product value contribute to the determination of optimum log size, and although log size can be modified greatly by

stand density (which can be modified by spacing and thinning), tree age (and thus rotation length) is also an important determinant. In areas that have a strong market for chips and pulp, relatively small pieces of wood can be harvested economically. Where there is only a saw log economy, only the larger stem sections may be harvested. If there is a market for bioenergy, even branches, foliage, stumps and large roots may have an economic value. Distance to market is also very important because of the effect of transportation costs on the value of a given log. Relatively small trees can be harvested economically close to mill or market, whereas recovery of even substantially larger logs may be uneconomic in forests far removed from mill or market.

The silviculture of tree crop production is clearly related to the end use of the crop and where the crop is being grown. This in turn influences the harvesting method and type of equipment used. Where log quality is important, such as where there is secondary manufacturing, tree crops must be grown in a manner that satisfies the market demand for quality.

4.2 Factors Affecting the Choice of Harvesting System

All other things being equal, the least expensive harvesting system is the one that will be used. However, things are not always equal. There are many factors that affect the acceptability, productivity, and economics of a particular piece of harvesting equipment, and thus the choice of harvesting system. Most of the types of equipment that are discussed in the following pages are "yarding" equipment; they remove the logs from the stump to the roadside. Other types of harvesting equipment not discussed here include felling equipment and the equipment used to load logs onto logging trucks or other transportation equipment.

a. Cost and Availability of Equipment

Although this is not a good reason for the choice of harvesting equipment in the long run, in some cases it may be an overriding factor. The very high cost of certain types of harvesting equipment (eg. helicopters), or simple lack of availability (eg. skyline systems), may result in the use of equipment that is either economically or environmentally sub-optimal, or both. However, in most cases an operator will purchase equipment according to the size of trees to be harvested, the topography, and other factors described below, rather on the basis of equipment cost alone. The economic performance of a particular piece of equipment will generally be more important than its cost of purchase.

b. Human Resources

Some types of equipment or harvesting method require highly skilled operators to make them work economically (eg. skyline yarders or horse logging). Lack of trained workers may sometimes exclude an

otherwise desirable or feasible method of harvesting, although retraining programs should be able to eliminate this particular constraint on choice of logging equipment. It may be necessary to offer higher wages to attract the skilled workers needed to make some harvesting systems operable (eg. uneven-aged harvesting).

c. **Safety**

Workers' safety will preclude the use of certain types of equipment on certain sites. Helicopter logging will be limited to areas where flying conditions are safe. Uneven-aged silvicultural systems (which involve selective or selection logging) in forests with large dead snags may be restricted by the Workers' Compensation Board. Restrictions limit the maximum slope on which ground skidders can be used because of operator safety considerations, as well as the operational limitations of the equipment.

d. **Tree Size, Quality, and Spatial Distribution**

Either very large or very small trees pose harvesting problems because of the weight of large logs, or the very high cost of cutting, processing and yarding small trees. Specialized equipment is required for the harvest of these extremes in log size. Open grown trees with large branches, trees with stem decay, low density stands, and stands with trees that are distributed very unevenly will often require different harvesting methods and equipment than dense stands of trees with small branches, decay-free stands, and stands that are uniformly stocked.

e. **Soil Type, Slope Stability and Topography**

Environmental considerations restrict (or should restrict) the use of skidders and other ground-based harvesting equipment on sites where they would compromise soil stability, soil structure and aeration, and slope hydrology. These restrictions are usually site specific, and are related to soil depth and texture, bedrock geology, slope, and rainfall. In steep, rocky, or broken topography, ground based systems may be impractical and only some of the cable or aerial systems may be technically feasible. Soil sensitivity will dictate the use of tired vs tracked ground-based equipment, and the size of both tires and tracks.

f. **Availability of Roads**

Where soil, slope and climatic conditions limit the density of roads and skid trails, long distance skyline or helicopter logging may be the only feasible harvesting method. Entire mountain slopes are logged this way in some typhoon-prone areas of Japan. However, this requires the necessary skilled manpower to operate these systems. Concern over the excessive road requirements of some

harvesting systems, especially those associated with summer logging in uneven-aged stands on steep slopes, may restrict the type of equipment which can be used.

g. **Distance to Mill or Market, and the Mill or Market Product Requirements**

The transportation and operational costs of some types of harvesting equipment may limit their use to within some economically-defined distance from the mill or market. Beyond this limit, less expensive methods may be required. The transport method (public roads vs private logging roads; land vs water transportation) that is available will influence the type of harvesting and transportation equipment used, as will the mill and market requirements. Where trees are taken to the mill as short logs, different equipment may be used in comparison to transporting entire tree stems in one piece ("tree-length" logging).

h. **Climate**

On very wet sites in cold climates, logging may be restricted to the frozen winter period, and will require equipment adapted for use at this time of year. If logging must be conducted during very wet periods, different equipment may have to be used in comparison to logging the same site in a dry period. Logging may be restricted to periods when the ground is covered by snow to protect regeneration, and the equipment used should be appropriate for winter conditions and the regeneration objectives.

i. **Silvicultural Considerations**

A harvesting system that leaves an area in a condition that results in excessive costs or environmental impacts in order to secure successful regeneration is unacceptable. Although the silvicultural implications of harvesting were largely ignored in the early days of B.C. forestry, an ecologically-based Pre-harvest Silvicultural Prescription is now required to ensure that the harvesting system used contributes to, rather than hinders, forest regeneration.

Clearly, there are several variables that determine the harvest method and type of equipment that either can be, or are, used. As a result, the optimum method or equipment for a particular site may sometimes not have been used in the past, and some sites have been harvested in a manner that is believed to do long-term site damage. An excessive proportion of a logged area in compacted and subsequently eroded skid trails, roads located and constructed in a manner that leads to slope instability and landslides, or the concentration of slope drainage resulting in downslope washouts

have all been caused by inappropriate harvesting practices in the past. In other cases, damage to the site may have been the result of poor road construction and maintenance, harvesting at the wrong time of year, or lack of operator skill, knowledge, or experience, rather than the wrong choice of harvesting method or harvesting equipment per se. The recent introduction of logging guidelines and the requirement for a Pre-harvest Silvicultural Prescription should result in a reduction in the frequency with which such harvest-related site damage occurs. Such damage has been the exception rather than the rule in most areas, but in steep topography and on compactable or erodible soils, far more soil damage has been caused than is acceptable.

4.3 Types of Harvesting Equipment

There is a wide variety of harvesting equipment, but the following is a brief description of some of the major types. The choice, or the actual method used, will be influenced by factors such as those listed above.

a. Horses

Horse logging has made a minor comeback as a low capital investment, low technology, "environmentally friendly" means of removing timber from the forest ("yarding"), especially in uneven-aged silviculture and in the commercial thinning of even-aged stands. With a skilled operator this can be an economic method of harvesting, but the lack of a large population of skilled horse operators will probably restrict this method to small scale, local operations. With the growth in environmental awareness, as more of the harvest comes from commercial thinnings, as rotations become shorter and tree sizes smaller, and as the number of private woodlots increases, horse logging may increase, but will probably remain a minor method of timber extraction. As with all methods of ground skidding in existing stands (thinning operations or harvesting in uneven-aged stands), there is concern about damage to the roots and stems of the remaining trees. Horse logging generally produces very little negative impacts on the soil, although significant compaction of skid trails can occur, especially with pairs of horses pulling heavy logs. Because it involves little or no use of fossil fuels, horse logging is desirable in terms of the "greenhouse problem" (in spite of the methane produced by horses!).

b. Skidders

Essentially large and powerful articulated tractors, skidders are a flexible and economical way of extracting timber. Their use on flat ground can result in a large proportion of the area receiving some soil disturbance. On steep slopes, an extensive network of skidtrails must be developed and a large proportion of the site may experience compaction and loss of top soil. Because they are

relatively cheap, skidders have been widely used, often on sites for which an alternative system with lower impacts on the soil would have been preferable. The use of oversize tires to reduce the pressure on the soil usually reduces soil impacts, but skidders generally have the reputation of being the most damaging method of harvesting in terms of physical impacts to the site. This reputation may not be fully deserved in British Columbia since much of the skidding is done in the interior in winter when frozen ground reduces the impact on the soil. However, there are far too many examples of summer skidder logging on steep slopes where extensive site disturbance and soil damage has been done.

c. **Tractors**

These are tracked vehicles of the bulldozer type. There is a considerable variety of types of tractor, including rigid-tracked "cats" (high ground pressure, less traction) and flexible-tracked "FMCs" (low ground pressure, better traction). Tractors can operate on steeper ground than skidders without the need for skid trails. On very steep ground they must operate on skid roads and this can result in severe site disturbance. They are often very heavy, but because of the large bearing surface of the tracks, their use can result in less soil disturbance than a skidder (especially the low ground pressure FMC type. See the comments above about skidders). Tractors share with skidders a relatively low capital investment (although larger tractors can be very expensive), and are relatively flexible in their use. Both skidders and tractors are unsuitable on fine-textured and moist sites, especially during wet times of the year, and on steep slopes. Of all the ground-based systems, large tractors of the "cat" type probably pose the greatest risk of soil damage if not used on appropriate sites in an appropriate manner.

d. **Forwarders, Feller Bunchers, Harvesters, and Processors**

This is a diverse category of equipment that varies from mechanized tree fallers, through equipment that picks up felled trees for transport to the roadside, to equipment that mechanically fells, picks up, delimbs, and stacks trees on the back of the machine for transport to the road. Because they are heavy when fully loaded with logs, forwarders and harvesters/processors can cause compaction on sensitive soils. They are more expensive than skidders and tractors, but can do the work of both fallers and skidders very efficiently (feller bunchers only do the job of the fallers); they are therefore economic to use. In the past, this type of equipment was restricted to relatively small trees and gentle topography, but newer models can cope with moderate slopes and much larger trees. They also require skilled operators. This type of multi-task equipment has been developed mainly in Scandinavia, but it is becoming increasingly popular in the Pacific-Northwest.

Where the slopes are too steep or unstable, the ground too broken or rocky, the soil too sensitive, or the logs too large, the so-called "ground-based" extraction systems (a-d above) cannot or should not be used. For such sites, there are several cable systems available (e-h below).

e. **High Lead**

This is a cable-yarding system in which a continuous loop of cable runs between the top of a spar tree (either a large standing tree whose crown has been removed or a metal tower, held vertically with guy wires) and a "back block" at the edge of the logging area. "Choker" cables connected to this main cable are attached to logs which are then dragged, while suspended from the leading end, to the landing area at the base of the spar. The position of the cable is moved progressively around the spar by moving the back block until all logs have been removed from a roughly circular area. Because no heavy equipment goes on the site, and because the logs are partially suspended, soil disturbance is generally much less than in the case of skidder or tractor systems. However, in the area close to the spar tree, or where the topography prevents the leading end of the log from being lifted off the ground, there can still be significant soil impacts, especially where very large, heavy logs are being yarded. High lead is considered to be a primitive and inefficient cable system with a high manpower requirement. Widespread use is almost unique to British Columbia, and this system is expected to decline in use over the next decade.

f. **Running Skyline (Grapple Yarder)**

Generally resembling a large tracked crane with a continuous loop of yarding cable out to a back block either mounted on a heavy tractor or attached to a stump, the grapple yarder picks up individual logs with a tong-like grapple and drags them partially suspended (fully suspended with lighter loads) to roadside or a landing. This system, which has a high capital cost, a low labour requirement, and requires a very skilled operator, is very efficient and produces relatively little damage to the soil. However, it generally requires a higher density of roads than the high-lead system because it can only reach out about 150m unless it is used in conjunction with a mechanical carriage, when it can reach 200 to 350m. The present B.C. stumpage system encourages the development of high road densities that permit the more economical shorter yarding distances. This increases the impact of this harvesting method on the site.

g. **Standing or Live Skyline Systems**

Based on systems developed in the steep and erodible mountainous terrain of central Europe, the standing skyline system has a carriage that rides up and down a fixed "skyline" stretched between the yarder and a back anchor or spar. A choker cable is

dropped from the carriage to the log and the log is then raised and carried fully suspended to the landing. By having multiple cable spans with intermediate supports, yarding can be conducted over very long distances. The impact of this system on the site is generally very slight. The system requires a skilled operator, is labour intensive, and problems have been encountered in switching from the more robust high lead and grapple systems to the somewhat more elaborate and delicate skyline system. A similar system, the live skyline, has been developed in the Pacific Northwest of the U.S. This system, which accounts for about 90% of the cable yarding in the P.N.W., also requires far less roading than grapple yarders (it can reach out 300 to 700m). It is relatively simple, highly productive and can carry higher loads than the standing skyline because it has a motorized carriage and the skyline can be raised or lowered during yarding. There has been little difficulty in switching from high lead to this type of skyline system.

h. **Helicopter and Balloon Systems**

Both helicopter and balloon systems have been used to replace high lead, grapple and skyline systems where there is a lack of roads or where the economics of these two systems is favourable. As in the complete suspension cable systems, the logs are lifted clear of the ground and the result is very little soil disturbance. Helicopter logging would be adversely affected by significant increases in the cost of fossil fuels; it is an energy-intensive harvest system. Both systems are weather dependent, strong wind and fog causing major constraints. However, they permit the harvesting of steep, inaccessible slopes, and helicopters have been used effectively in selection logging and in removal of large trees from sensitive riparian areas. They are both a very expensive method of harvesting, and require fairly large patches of high volume, high value timber to render them economic. The economic factor limits their application in selective logging and thinning, especially on steeper slopes.

4.4 Roads and the Environmental Impact of Harvesting

The impacts of harvesting on soils are discussed in some detail in Chapter 6, but it is worth re-iterating a point that was made earlier: that many of the environmental problems associated with timber harvesting are related to the associated roads.

A road network is an intimate part of any harvesting system. It is also essential for access for forest protection and silvicultural operations, and can have many benefits for forest recreation. "Mainline" or major haul roads are generally well built and maintained; it is in the economic interests of a company to do so. Unfortunately, secondary roads, spur roads, and other temporary roads have sometimes been poorly constructed, poorly located, poorly drained with inadequate culverts, poorly maintained, and poorly "put to bed" for the period of several

decades between their use for silvicultural or other management activities.

The high cost of roads and the danger of windthrow encouraged the practice of "progressive" clearcutting of valleys and ridges in the past. In this practice, new clearcuts were created adjacent to the previous clearcut, thereby creating progressively larger openings, but minimizing the length of new road construction, the total length of the road system, and the associated environmental problems. Progressive clearcutting can be aesthetically unattractive and cause wildlife problems. In some climates and with some forest types it can cause natural regeneration problems and result in significantly-altered hydrological regimes (river flows) and fish habitat.But it can certainly reduce the extent of road-related problems, or at least the costs of preventing them. Where clearcuts are small and elongated, "progressive clearcutting is no different from strip clearcutting". This is a widely used and well respected silvicultural system in Europe. The topic of the dispersion of clearcuts will be discussed later (Chapters 6 & 7).

The introduction of the Coast Logging Guidelines in the early 1970's terminated the practice of progressive clearcutting on the coast, and replaced it with a system in which only 50% to 60% of a valley would be logged on the "first pass". Once these areas have regenerated ("greened up"), the remaining areas may be harvested, subject to constraints for wildlife or other resources. More rapid removal of these remaining stands may be permitted in cases of windthrow, fire, or insect attacks. If the green-up period is short, a valley may look much the same after the second or third "logging pass" as it would at the same time after a progressive clearcutting system, and the effects on other resource values may be similar. Where the green up period is long, causing the different logging passes to be spread over much of the rotation, the area will have a mosaic of different aged stands.

There is increasing public pressure to move away from clearcut harvesting and to replace it with uneven-aged management and selection harvesting. What is sometimes not understood by the proponents of this change is that although such a policy may make the landscape look nicer over the ten to twenty year post-harvest period, it generally requires a substantial increase in the road network in comparison with cable-yarded clearcutting. Accompanying the increased roading there is usually an increased risk of site and environmental damage. This is particularly true in steep mountain topography where up to a third of the site may be occupied by skidroads if ground-based yarding is the method of uneven-aged harvesting. In contrast, clearcutting with cable yarding may require as little as a few percent of the area in roads.

4.5 Conclusions

There are many factors that determine the harvesting system that

is used on a particular site. Economics and the availability of equipment and trained operators appear to have been factors that in the past have sometimes resulted in the use of systems that were sub-optimal in terms of protecting and sustaining resource values, both timber and non-timber. Practical considerations will always play a role in choice of equipment, but with the development of the requirement for a Pre-harvest Silvicultural Prescription there are now much stricter controls on what harvesting systems and equipment are acceptable and permissible on a particular site. Where practical considerations prevent the use of "environmentally-sound equipment", areas should be deferred from harvest until the appropriate equipment is available and/or economical. Once again it should be noted that in many cases, damage to steep slopes is more closely related to the location, construction, and maintenance of roads than to the actual type of harvesting system used. Because so many of the environmental problems associated with harvesting are attributable to roads, increased emphasis should be given to long-reach cable systems or other systems that minimize the length of road required, subject to future access requirements for protection and silviculture. The manner in which a particular piece of equipment is used is also important.

CHAPTER 5. ECONOMIC CONSIDERATIONS IN THE SELECTION OF THE METHOD OF FOREST HARVESTING

Brief reference to the relative costs of different methods of harvesting were made in Chapter 4, but the importance of the topic warrants a more detailed discussion. Timber management, as opposed to most other aspects of forest management, is first and foremost an economic, revenue-generating activity. Forest products must be sold in an increasingly competitive global timber market, and as coastal British Columbia's traditional advantage of high quality, unmanaged, accessible, old-growth forest declines, and with increasing haulage distances and lower volumes per hectare in the interior, the need to reduce costs and increase efficiency will only increase. Economics will therefore continue to play an important role in the choice of harvesting method, except where the objectives of management require that a silvicultural system and harvesting method are to be used irrespective of the implications for the economics of harvesting. The Pre-harvest Silvicultural Prescription and the increasing consideration given to non-timber values will probably result in an increase in the frequency with which economic considerations are given reduced emphasis in this decision.

5.1 Relative Costs of Harvesting by Different Methods

Harvesting costs depend on many factors, including slope, the evenness of the terrain, average log size, the density of roads (ie. the yarding distance), the volume per hectare, the volume harvested, the location of the site, and the type of logging equipment. Figure 5.1 shows the relationship between logging costs and six factors that affect the economics of logging. These relationships were devised for coastal B.C., but the general shapes of the relationships are also valid for the interior.

The economics of harvesting is very sensitive to the volume to be harvested per hectare. There are many infrastructure costs (roads, landings, camps) that do not change as the volume removed from a harvested area changes, so that as the volume harvested decreases, the infrastructure and overhead costs per m^3 increase in proportion. The cost of operating harvesting equipment may also be relatively unaffected as the volume harvested per hectare changes. Consequently, as the volume harvested per unit area declines, the cost per m^3 of removing cut trees will increase. Partial cutting and uneven-aged systems are therefore much more marginal economically than clearcut systems. Depending on the haul distance to the mill, many valleys that can be managed economically under an even-aged clearcut system would become economically inaccessible if managed under a partial cutting, unless there was an adjustment in the stumpage system to account for the increased logging costs. This is particularly true in the rugged terrain of the coast where roading costs are so high, but it is equally true, if less critical, in much of the interior. If the economics of the

entire tree crop production cycle are considered in a single calculation, these increased harvesting costs may be offset by reduced planting and site preparation costs. Where the economic calculations are limited to the harvest phase of silviculture alone, partial cutting is more costly.

Because of the complexity of the economics of harvesting, it is very difficult to compare harvesting costs between different types of equipment. Furthermore, many of the harvesting systems are not interchangeable, reducing the value of comparisons. For example, horse logging is not an alternative to high lead yarding, whereas grapple yarding is an alternative to high lead. Skidders and tractors may also be interchangeable. In these latter examples, cost comparisons are more valid.

Table 5.1 illustrates the effect of log diameter on logging costs for three different harvesting situations on the coast, and, for comparison, average interior costs for skidder logging. The much higher cost of logging on the coast is one reason why the more economical even-aged management is favoured over uneven-aged management in this part of the province. Other reasons for clearcutting on the coast have been silvicultural, ecological, and practical. Table 5.2 illustrates how variable costs can be within one type of equipment (helicopters in the example), and Table 5.3 shows how helicopter costs compare with "conventional" harvesting. Table 5.4 shows some of the detail of the economics of the harvesting operation.

These examples should serve to show that, as with silvicultural and ecological evaluations of forest harvesting, the economics of harvesting is complex; it is site and situation-specific, and not susceptible to many useful generalizations. Economic-inputs to decisions about which harvesting method or type of equipment will be used therefore require a site-by-site evaluation. Some examples of useful case-study comparisons are:

MacDonald, A.J. 1988. A case study of roadside logging in the central interior of British Columbia. Forest Engineering Research Institute of Canada, Vancouver, B.C. Technical Report TR-87.15pp.

Hedin, I.B. 1980. Comparison of two logging systems in interior British Columbia: Central Processing Yard vs Conventional. Forest Engineering Research Institute of Canada, Vancouver, B.C. Technical Report TR-45. 53 pp.

Rogers, R.E. & A.J. MacDonald. 1989. Ground skidding second-growth timber in coastal British Columbia: a case study. Forest Engineering Research Institute of Canada, Vancouver, B.C. Special Report No. SR-60.

Bell, T. 1990. The feasibility of horse logging. Unpublished essay. Available from Dr. David Haley, Faculty of Forestry, U.B.C.

Sauder, B.J. & M.M. Nagy. 1977. Coast logging: high lead versus long-reach alternatives. Forest Engineering Research Institute of Canada, Vancouver, B.C. Technical Report No. TR-19. 50 pp.

5.2 Economics of Second Growth Harvesting in Comparison to the Harvesting of Old-Growth and Previously Unmanaged Forests

Managed second growth forests will differ from old-growth and other unmanaged forests in several ways that will affect the economics of harvesting. The extent of the difference will be greater for even-aged than for uneven-aged second growth, but in both systems the fact that roads will already be in place will be the major economic factor.

There will generally be fewer large decaying logs, stumps and snags to impede the movement of logging equipment in conventionally-managed even-aged second growth than in old-growth forests. This should reduce logging costs. The trees being harvested will probably be smaller, permitting the use of smaller, less expensive equipment that may have less negative impacts on the soil, but raising the costs of yarding because of log size considerations. However, because the size of logs will be much less variable, more mechanized and efficient harvesting systems will be used, offsetting the effects of reduced piece size. The trend will probably be towards greater use of multi-function mechanized ground-based systems on sites that are not too steep. On the most productive coastal sites, large tree size will probably still require the use of manual felling and cable extraction systems. In steep mountainous sites, cable or helicopter/balloon systems will probably still be used.

Because the size of trees harvested in uneven-aged second growth stands will be smaller than in old-growth stands, the costs of harvesting per m^3 will increase. Similarly, if the volume per hectare in the stand is reduced, either by the frequency and intensity of harvest or by a dense network of skid trails and damage to residual trees, harvesting costs per m^3 will increase. On the other hand, the frequency of large logs and snags will probably decline in comparison to old-growth (unless it is a management policy to retain a supply of these), thereby reducing the difficulty and costs of harvesting. Otherwise the economics of harvesting may not be very different between uneven-aged old-growth and uneven-aged second growth forest.

It is expected that harvesting costs will be higher in second growth uneven-aged forests than second growth even-aged forest because of the lower volumes extracted in any one harvest and the greater care required to avoid damage to the remaining trees. However, as already noted this may be offset by reduced site preparation costs, natural regeneration rather than planting, and a more frequent harvest which may reduce carrying costs on

Figure 5.1

Relationships between logging cost ($/m3) and six factors that affect the economics of logging: a, the infrastructure costs; b, various overhead costs; c, central administrative overhead; d, yarding costs; e, hauling costs (transportation to the mill); and f, sorting and scaling costs. The effects of these factors and the degree of logging difficulty on logging cost is expressed as a function of volume per hectare, distance to the mill or camp, and mean log volume. (Source: Kellogg, R.M. 1989. Second growth Douglas-fir: its management and conversion for value. Forintek Canada Corp. Special Publ. SP32 ISNN 0824-2119, Vancouver, B.C. 173pp.)

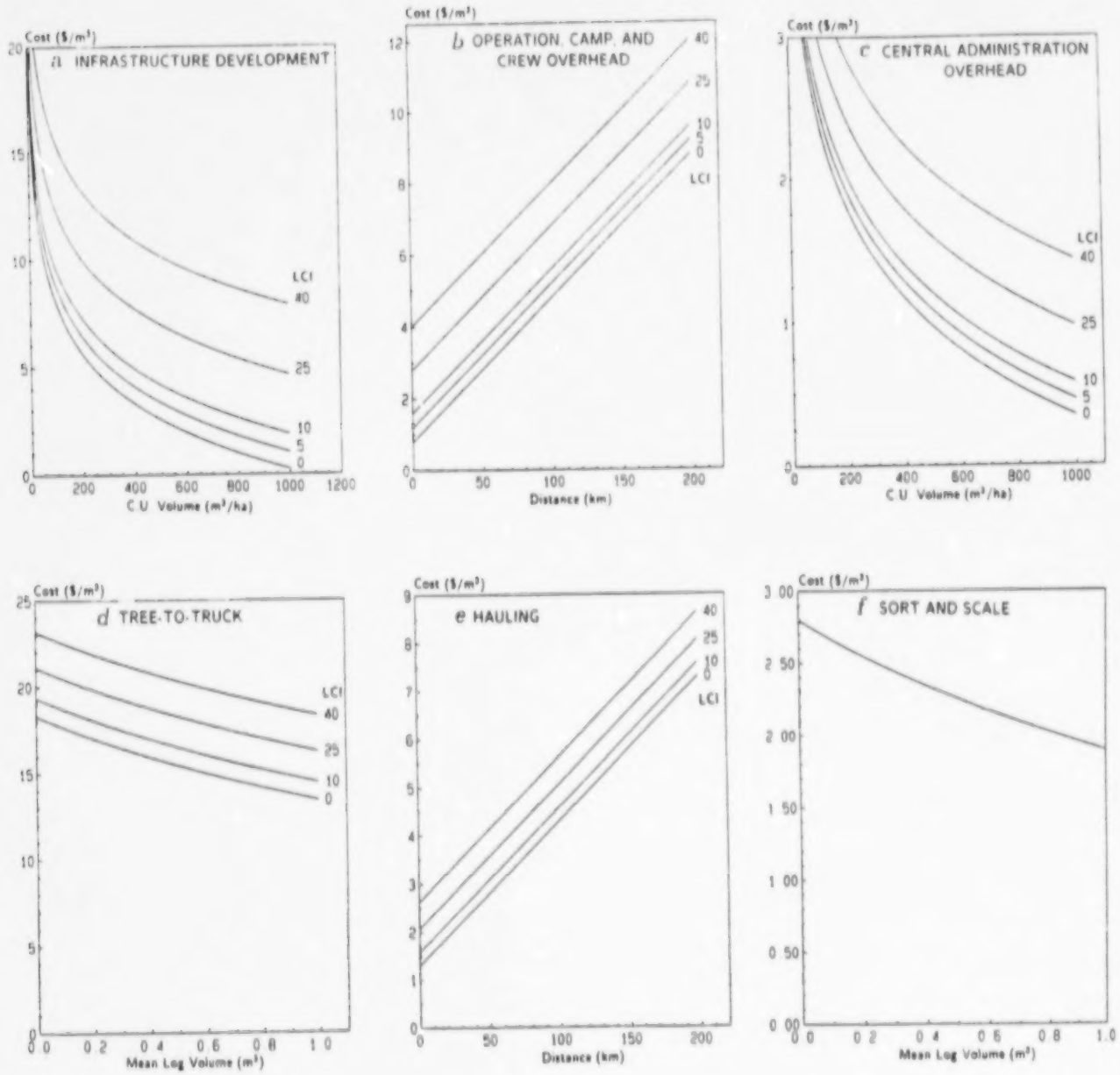


Table 5.1

The effect of average log size (diameter) on average logging costs (m3/ha) in three different harvesting situations in coastal British Columbia, and an average for interior skidder logging (Source: Nawitka Resource Consultants, 1987. Impact of Intensive Forestry Practises on Net Stand Values in B.C. FRDA Report 014. Forestry Canada, Victoria. 78 pp. + app.)

LOGGING COSTS
(Cost of felling and bucking, yarding, and contracting overhead)

AVG DIA (cm)	1	2	3	4
			$/m^3	
16	20.00	38.90	44.90	12.00
18	18.50	33.90	39.90	11.00
20	17.00	27.40	31.90	10.00
22	16.00	24.40	27.90	9.50
24	15.00	20.90	23.90	9.00
26	14.00	18.40	20.90	8.50
28	13.50	17.90	19.40	8.50
30	13.00	16.40	17.90	8.50
32	12.75	15.90	16.90	8.25
34	12.50	15.40	16.40	8.25
36	12.50	14.90	15.90	8.25
38	12.25	14.40	15.40	8.25
40	12.25	13.90	15.15	8.25
42	12.00	13.65	14.90	8.00
44	12.00	13.40	14.65	8.00
46	11.75	13.15	14.40	8.00
48	11.75	12.90	13.90	8.00
50	11.50	12.65	13.65	8.00
52	11.50	12.40	13.40	8.00
54	11.25	12.15	13.15	8.00
56	11.25	11.90	12.90	8.00
58	11.00	11.65	12.65	8.00
60	11.00	11.65	12.65	8.00

1 - Coast: Valley bottoms, little slope, fairly even terrain; may be skidder logged or grapple yarded.

2 - Coast: Valley sides, combination of slope and terrain medium; would likely be grapple or high-lead.

3 - Coast: Valley sides, combination of slope and terrain difficult; some grapple but mainly high-lead.

4. - Interior: Average conditions - skidder logging.

Table 5.2

Variation in the yarding cost ($/m^3 between different types of helicopters. (Source: Dr. David Haley, Forest Economist, Faculty of Forestry, University of British Columbia.)

Helicopter	$/m^3	Max. load (lbs/trip)
Boeing CH135	48.3	28,000-30,000
Sikorsky S64E	40.0	20,000
Kawarski V.107	36.4	10,000-12,000
Sikorsky S61N/L	34.5	7,500-10,000
Aero-Speciale Puma	40.0	10,000
Bells 212+214	33.3	2,500-3,500

silvicultural investments. Clearly, economic comparisons between even-aged and uneven-aged systems are complex. The economic evaluations should be conducted on the entire rotation-length silvicultural systems and not just on the harvest phase of silviculture.

Table 5.1

Comparison of the costs ($/m^3) for various phases of harvesting between helicopter and "conventional" harvesting. (Source: Dr. David Haley, Forest Economist, Faculty of Forestry, University of British Columbia.)

PHASE	HELI-LOG VS. CONVENTIONAL	CONVENTIONAL $/m	HELI-LOGGING $/m
Engineering and Forestry	Helicopter lay-out and silviculture. Intensity of lay-out will increase costs 25% to 50%.	1.25- 2.50	2.25- 3.00
Falling	Helicopter falling requires more experience and care in bucking to weight and limbing of trees.	3.50- 4.50	5.00- 7.00
Yarding	The major cost difference occurs here. Average cost used for grapples and towers.	10.00-15.00	30.00-50.00
Loading	These phases are actually a little lower in helicopter situations due to better logs and increased volumes.	5.00-10.00	4.00- 9.00
Dryland Sort	These phases do not vary.	6.00-15.00	4.00- 9.00
		25.00-47.00	47.00-85.00

The above costs do not include:
1) Overheads fixed
2) Overheads Variable
3) Profit

Table 5.4

Detailed breakdown of the costs of typical coastal harvesting (source. Dr. David Haley, Forest Economist, Faculty of Forestry, U.B.C.)

PHASE	AVERAGE COST 1987 $/m^3	
DIRECT COSTS		
FALLING & BUCKING	$ 3.50	
YARDING/SKIDDING		($ 7.00)
LOADING		($ 3.00)
WEIGHTED AVE YARD & LOAD	$ 9.00	
TREE TO TRUCK		($12.50)
HAULING	$ 4.70	
DUMP/SORT/BOOM	$ 4.70	
CAMP COSTS	$ 1.50	
CREW TRANSPORT	$ 2.50	
ROAD MAINTENANCE	$ 1.60	
TOW & BARGE	$ 2.70	
TOTAL DIRECT	$31.00	
INDIRECT COSTS		
CAMP OVERHEAD	$ 3.70	
STUMPAGE/ROYALTIES/CHARGES	$ 7.30	
ROAD CONSTRUCTION	$ 5.40	
TOTAL INDIRECT	$16.50	
HEAD OFFICE OVERHEAD	$ 4.60	
TOTAL DELIVERED COST	$51.70/m^3	
FORESTRY 1984 $/m^3		
ENGINEERING	$ 0.60	
CRUISING	$ 0.13	
WASTE SURVEYS	$ 0.03	
FALLING RESIDUALS	$ 0.03	

CHAPTER 6. TIMBER HARVESTING AND ENVIRONMENTAL CONCERNS

The overall impacts of timber harvesting on the forest ecosystem can be summarized in terms of the effects on soils, the effects on microclimate and the effects on living organisms. Each of these is discussed in general terms in this section of the paper, followed by a discussion of the speed of ecosystem recovery from harvest-induced disturbance. Impacts on specific resource values are summarized in Chapter 7. As already noted, some of the environmental impacts that have been attributed to harvesting may in fact be caused by the associated road building, and others by post-harvest site treatment. The relative importance of the actual harvest impacts will be commented on at the appropriate points in the discussion.

6.1 Impacts on Soils

The effects of timber harvesting can be considered under the following topics: soil organic matter, soil nutrients, soil architecture and aeration, soil biology, soil hydrology, and soil stability.

a. Soil Organic Matter

Soil organic matter accumulates in forests over time because the inputs of organic matter by root death, above ground litterfall and plant death exceeds the rate of organic matter loss by decomposition. Forests tend to accumulate an organic layer on the soil surface because of this excess of inputs over outputs. Similarly, humus accumulates in the mineral soil because the very slow mineralization of humus is exceeded by the production of humus from the decomposition of fresh organic matter. Following harvesting, especially clearcut harvesting, litter inputs are temporarily reduced or eliminated, while decomposition/mineralization rates are usually accelerated. The result is a fairly rapid loss of organic matter, and unless a logged area is revegetated, all the organic matter will eventually disappear. Normal processes of successional recovery usually result in revegetation before this occurs, so that although soil organic matter does decline following harvesting, it usually starts to accumulate again within one or two decades. The extent of organic matter accumulation in the uncut forest, and the extent of its loss following harvest, are highly variable between the many different forest types in British Columbia.

In addition to decomposition-related losses, harvesting removes organic matter in the form of harvested materials that would otherwise eventually have contributed to soil humus. Erosion, mass wasting, and the construction of landings and skid trails remove organic matter from one part of the harvested area and deposit it in another. Where the denuded area is small (discontinuous patches less than a few metres in diameter), the long-term effect on site

productivity may be negligible. Where displacement occurs over many metres, or even tens of metres, long-term site degradation may occur. If it becomes buried, the displaced organic matter may undergo accelerated decomposition compared with that of undisplaced organic matter. The resultant accelerated nutrient release may lead to nutrient loss unless the combined plant nutrient uptake and soil nutrient storage capacity in the depositional area are able to retain all the nutrients on the site.

Post-harvesting slashburning results in a short-term rapid loss of the organic matter contained in logging slash and forest floor. However, in warm humid forests much of this organic matter will be lost over the next decade or two through decomposition even in the absence of fire. The major difference is the rate of loss. This has significance for site nutrient balance (discussed below).

b. Soil Nutrients

Most of the actively circulating nutrients in forests exist in organic matter. Nutrients are lost in harvested materials, the extent of the loss depending on the proportion of various different tree biomass components that is removed. Whole-tree harvesting (all above ground tree biomass) can remove as much as four times as much nitrogen and phosphorous as conventional stem harvesting because foliage and branches have much higher nutrient concentrations than woody stem tissues, and consequently tree canopies contain a disproportionately large amount of nutrients relative to their biomass.

Nutrients originally contained in the organic matter that is lost by post-harvest decomposition are released to the soil. Where this decomposition is rapid, there is a flush of nutrient release called the "assart". Unless the combination of nutrient uptake by trees and non-crop vegetation and the action of the soil nutrient exchange capacity are able to take up and hold this flush of nutrients, much of it (especially nitrogen) may be lost from the ecosystem. This loss may be by leaching and/or denitrification (a gaseous loss in which non-gaseous forms of nitrogen are turned into various gaseous oxides of nitrogen).

Nutrient loss caused by harvesting is thus a function of the amount and type of biomass removed by harvesting, the extent and rate of post-harvest organic matter decomposition, the site's soil exchange capacity (the ability of the soil to withdraw nutrients from soil solution and hold them in a form that does not prevent their uptake by plants, but reduces their loss by soil leaching), the rate of revegetation, and the nutrient uptake by this vegetation.

Nutrient loss, especially of nitrogen, can be greatly increased by post-harvest slashburning, although there is some evidence that substantial losses of nitrogen may occur by denitrification in some types of forest following harvesting even if the area is not

burned. If the fire delays the development of the plant community, further nutrient losses can occur by soil leaching. Where slashburning is light to moderate, and where it reduces the time taken to reforest a harvested area (which it often does), it may actually result in a reduction in overall nutrient loss by increasing the growth and nutrient uptake of trees and other vegetation.

By accelerating organic matter decomposition and by reducing the growth and nutrient uptake of non-crop vegetation, mechanical site preparation and herbicide treatment can also accelerate nutrient loss by soil leaching. However, if these site treatments accelerate tree growth and cause earlier occupancy of the site by a new forest, they may result in reduced nutrient loss over the rotation.

The relative magnitudes of harvest-induced nutrient loss and loss caused by various different post-harvest site treatments will vary greatly from case to case. It is difficult to develop useful generalizations, but losses in harvested materials or due to slashburning are usually significantly greater than soil leaching losses. As noted above, denitrification can apparently cause as great a loss of nitrogen as does slashburning under certain circumstances, except that the loss occurs over several years rather than several minutes.

c. **Soil Structure**

Adequate soil aeration is almost as important as adequate nutrition for the growth of many forest tree species. The roots of most species must have a supply of oxygen, and without an adequate root system plants cannot grow. Soil aeration depends on the presence of a network of soil air spaces ("pore space") which in most soils depends on soil structure: the "architecture" of the soil - how all the physical components of the soil are assembled in space. Just as a building is no longer a building when it is reduced to a pile of bricks, soil whose architecture has been crushed by heavy equipment or destroyed by erosion is no longer really soil. Soil in which aeration depends on soil structure generally cannot support most forms of plant and animal life following the loss of structure; these life forms are excluded until some structure has been redeveloped. Soil structure depends on the presence of soil organic matter (the "mortar" of the soil "building") and the activity of roots and soil organisms.

Soil structure is relatively easily damaged by the passage of heavy equipment, especially when the soil is wet. The damage is more serious in fine-textured than in coarse-textured soils, and is more persistent in warm climates that lack freezing and thawing of soil than in areas that have soil frost.

Soil structure can be damaged by an extremely hot slashburn which

destroys soil organic matter, but most of the physical soil damage that occurs is the result of ground-based yarding activities. Helicopter and most horse logging pose the least harvest-related threat to soil structure. Cable logging with partial-suspension of the logs is intermediate.

d. **Soil Biology**

The soil can be considered as an ecosystem in that it satisfies all of the criteria that define the term ecosystem: structure, function, complexity, and change over time. It differs from an entire forest ecosystem in that it lacks a mechanism for the continuous input of energy: this is provided almost entirely by the litterfall of green plants that constitute the driving force of the forest ecosystem. The structure of a terrestrial ecosystem includes an atmospheric component, a soil component, and a biotic component. The biotic component of the soil includes plants (mainly roots), animals, and microbes. Living organisms are a vital component of the complex system that we call soil. They create and maintain soil structure. They process dead soil organic matter, releasing nutrients and producing humus. By continually mixing the soil, they determine soil development. Soil organisms thus play a major role in maintaining soil as a suitable substrate for plants.

Forest harvesting affects soil organisms in a variety of ways. By killing tree roots that are associated with certain soil fungi, the abundance of these fungi is reduced, and this permits an increase in bacterial populations. This in turn favours the soil animals that feed on bacteria and promote bacterial abundance (eg. earthworms), which may increase in numbers and activity and cause an acceleration in decomposition of the forest floor (the "assart" effect). The increased summer warmth of the forest floor following harvesting may also favour increased soil animal activity. Increased soil animal and soil bacterial activity is usually associated with increased soil fertility.

Above-ground litterfall and fine root death provide the energy source for soil organisms, and when all the easily-decomposed logging slash and litter has been decomposed, the abundance of soil organisms may decline. However, the harvested area has normally been invaded by pioneer vegetation by this time, providing an input of highly decomposable litter that sustains the elevated activity of the new assemblage of soil organisms. Eventually, as succession returns the area to its original forest condition, the original abundance and composition of the soil biota is restored.

The period of altered microbial and soil faunal activity that follows the disturbance of harvesting can have lasting beneficial effects on soil structure and fertility. In cool, humid climates (such as many coastal B.C. forests), soils that have not been disturbed for a long time may exhibit reduced rates of organic

matter decomposition and a slowing down of nutrient cycling. As soil temperatures decline as one travels north, decomposition becomes even slower, greatly limiting tree growth and forest development. The physical and microclimatic disturbance to these soils caused by timber harvesting, windthrow or wildfire can re-invigorate these soil processes, improving soil fertility and increasing site productivity.

On the other hand, if harvesting causes soil compaction, erosion and the loss of soil organic matter, the abundance and activity of soil organisms will be greatly reduced, and this will slow the recovery of the ecosystem from the logging disturbance. Harvesting that leaves the soil's structure and organic matter intact and permits rapid re-vegetation will generally benefit soil biological activity and may improve soil conditions for subsequent tree growth.

e. **Soil Hydrology**

The ability of water to infiltrate into soil is a function of soil texture and soil structure. Once water has entered the mineral soil, it moves downslope slowly through the larger soil pores ("macro pores") and old root channels (spaces where roots used to be but have died and decomposed leaving a hollow "pipe" in the soil), and does not normally cause any erosion or landslides. The presence of an organic forest floor protects the structure of the surface mineral layers and promotes infiltration. Compaction, or the loss of surface soil structure following the removal of the forest floor and exposure of the mineral soil to heavy rain, reduces infiltration rates and leads to surface run-off. If this surface water is allowed to gain enough speed and volume, it may gain sufficient energy to cause erosion. This in turn can lead to gullying, sheet erosion, and possibly to a "debris torrent": a rapidly moving mass of soil, rocks and logging slash. Such torrents can do considerable damage to the site and to any streams they enter. Debris torrents can also occur where harvesting deposits a lot of slash in gulleys. During periods of intense rain, rain-on-snow, or rapid snowmelt, this slash can wash into streams causing debris jams. If these burst, they can become damaging debris torrents.

The concentration of water within the soil mantle caused by the convergence of compacted skid trails on steep slopes, or by inadequate culverting on roads, can result in the saturation of soil downslope. This is a common source of landslides because the saturation reduces the friction that holds the soil on the slope. The soil literally "floats" downslope.

f. **Slope Stability**

As just mentioned, the stability of soil on steep slopes is a

function of the friction between the soil and the underlying material, and the action of gravity trying to pull the soil downslope. It is also a function of the strength of the roots of trees and other plants which act to tie the soil to the slope. Alteration of slope hydrology can lead to localized soil saturation, a reduction in the friction, and a loss of slope stability. However, the roots may still provide sufficient anchorage to prevent a landslide. Following harvesting, the roots of the cut trees slowly decay and lose strength. As this occurs, the soil anchorage they provide also declines. The regrowth of shrubs and trees following logging provides new live roots which gradually replace the declining anchorage provided by the old dead roots. However, if the regrowth of new roots does not keep pace with the loss in strength of the old roots, the total contribution of roots to slope stability will decline for several years after logging before recovering to its old value. If there are heavy rainstorms during this period of reduced total root strength, landslides may occur on steep slopes. The critical period of instability is often between ten and twenty years after logging, but may be as early as five years post-harvest. Obviously, this is likely to be more of a problem in clearcuts than partially-cut forests, although where the latter have an increased length of roads and skid trails, the total affect on slope stability may in some cases not be very different.

6.2 Effects on Microclimate

By intercepting sunlight, tree canopies create a cooler and more humid microclimate within the forest. Wind speed is also reduced. In cold, northern climates, this may result in such low soil temperatures that nutrient cycling is inhibited and forest productivity declines. Periodic disturbance by fire, wind or logging causes a warming of the microclimate, invigorates soil processes, and raises forest productivity. In contrast, the forest microclimate in hot, dry forests in southern B.C. may be essential for the successful regeneration of trees and shrubs. The microclimate of clearcuts in such forests may be so hot that only grasses and semi-desert species can become established. Between these two extremes are forests in which the forest microclimate is both less inhibiting to soil processes and less critical for regeneration.

The insulating properties of a tree canopy protect seedlings in a forest from "radiation frosts" - below freezing temperatures caused by radiant cooling of the ground surface in a clearcut or natural opening. If mineral soil is exposed in the clearcut, release of heat from the soil can counteract this radiant cooling. However, a layer of herbs (eg. grasses) or an undisturbed organic forest floor can insulate the mineral soil, restricting the release of heat and thus contributing to the development of damaging radiation frost. This is more of a problem in clearcuts than in partially-cut forests because of the microclimatic protection afforded by the

remaining overstory.

Clearcut harvesting temporarily removes the forest microclimate, except near the edge of the uncut stand where the "microclimatic shadow" of the standing trees still maintains an influence. The change in light, humidity, wind and temperature following harvesting favours the early successional species that are adapted to these conditions. The result is a characteristic assemblage of early successional herbs, shrubs and pioneer trees. The greater the change in microclimate, the greater the change in plant species. As this early successional community grows in height and leaf area, it creates a sheltered microclimate beneath its canopy, recreating the microclimatic conditions favoured by the later successional species. Thus, microclimatic change plays an important role in the successional changes that accompany ecosystem disturbance and recovery.

Because the forest microclimate reverts to its original condition as the forest regrows, the persistence of harvest-induced changes in microclimate are generally related to the factors that determine vegetation regrowth, such as soils. However, in very hot and dry climates, in situations where "frost heaving" of exposed soil delays revegetation, or where harvesting creates "frost pockets" or promotes radiation frosts, the altered microclimate itself may play a major role in the patterns and speed of successional recovery. This is also true in coastal subalpine forests close to tree line, where the presence of a large tree stem creates a "thermal island" which causes earlier snow melt around it and improved seedling growth within this modified microclimate. If all the "thermal islands" are removed by clearcutting, early plantation growth in these high elevation forests may be significantly slowed until the trees are taller than the average depth of the winter snowpack. High stumps, dead trees, or even large rocks can also create "thermal island" microclimates in their immediate vicinity.

6.3 Effects on the Biota

Forest harvesting creates successional disturbance: one or both of the soil and microclimatic components of the seral stage are altered to conditions typical of an earlier stage in succession. The extent of the change is proportional to the extent of the canopy removal (ie. even-aged vs. uneven-aged management) and the degree of soil disturbance.

As the physical and chemical characteristics are changed by disturbance, there is a change in the composition and abundance of animal, plant, and microbial communities. Those species that are completely dependent on the ecological conditions that prevailed in the unharvested forest will be lost from the harvested area, and some species may even be lost from the area of the remaining uncut forest that is within a hundred metres or so of a clearcut. Some

old-growth species will adapt to, or simply tolerate, the clearcut conditions, and remain in reduced abundance until the forest regrows. Other species, which either require or benefit from the earlier successional conditions of the harvested area, will increase in abundance. Many animal species will do best when they have access to a mosaic of different seral stages: a mixture of freshly harvested areas, young forests of various ages, and patches of old or unmanaged forest.

Use of clearcuts by wildlife species is not merely a function of food. Animals also require shelter for security, protection from predators, and protection from the thermal extremes of sun, wind, and rain. Thus, large clearcuts that lack adequate cover and shelter may not be used by some species of wildlife even though there may be abundant nutritious plant food for them in the clearcut. Clearcuts may also be a problem for large, ungulate, herbivorous species in the winter. Heavy snowfalls may make it impossible to traverse clearcuts or find food, whereas in old growth forests the fall of branches and lichens provide food, and the interception and redistribution of snow by the tree crowns reduces snow depth and uniformity.

The effect of forest harvesting on the plants, animals, and microbes of the forest is highly variable and cannot, therefore, be generalized. It will depend upon the particular type of forest, the extent and intensity of successional change caused by harvesting, and the ecological requirements and tolerances of each species in the area. Clearly, if forest harvesting results in a prolonged delay in regrowth of vegetation, both animals and microbes will be adversely affected because of a lack of the food provided by plants and plant litterfall, and the lack of shelter for animals. Where harvested areas revegetate rapidly, the normal successional sequence of plant, animal, and microbial communities that is characteristic for the site may be expected to occur.

If all the original forest is removed from a large area (such as in a very large, very hot midsummer wildfire covering tens or hundreds of thousands of hectares), the process of successional recovery may be very slow because of the lack of plant seeds, microbial propagules and animals to recolonize the area. Only in extensive, contiguous areas of clearcut harvesting followed by severe slashburning would one expect harvesting to produce a similar result. Such harvesting practices did occur in some parts of British Columbia in the past but are no longer permitted, except possibly in the salvage of a large insect-killed tract of forest. However, it is unlikely that such areas would be slashburned, or, if burned, that they would be burned severely. Most harvested areas become populated with a variety of plant, animal and microbial species in the absence of site preparation treatments, including species that were present prior to harvesting and species that invade the site after harvesting. The balance of these is usually altered by site preparation.

6.4 Ecosystem Recovery from the Impacts of Harvesting

An accurate evaluation of the ecological impacts of harvesting or other silvicultural and management activities cannot be made simply by inspecting the degree of soil disturbance, microclimatic change, and biological alterations to the site immediately after harvesting has been completed. Such an approach may either underestimate or overestimate the rotation-length consequences of these impacts. Many evaluations of harvesting have been largely based on the visual appearance of the site, rather than on an understanding of how the ecosystem processes of recovery have been affected. The fact that a harvested site may look ugly may be unacceptable if maintenance of the visual quality of every harvested area at all times is an important management objective. However, the visual appearance of a site should not influence the evaluation of the ecological impacts of harvesting on the site.

If the size, shape, orientation and location of the harvested area are determined according to the principles of visual resource management, the fact that a freshly logged area does not look nice in close-up may not threaten the overall visual quality of the landscape. The frequent showing by environmentalists of pictures of freshly logged or slashburned sites "frames" the generally ugly visual image of this stage of the silvicultural cycle and "hangs" it in the back of people's minds, unchanging like a picture on the wall. Ecosystems do not remain static. They recover from disturbance. Such images give a very incorrect impression of the medium and long-term impacts of forest harvesting, both visual and ecological.

The rate of ecosystem recovery from harvesting will vary according to the climate and the soil conditions. Recovery from disturbance is slow in excessively hot, cold, wet or dry climates. It is slow on very nutrient poor sites, on soils that are excessively drained (ie. the soil gets dry, irrespective of the climate), soils that are waterlogged, and where the soil lacks structure and aeration. In humid climates that lack temperature extremes, and on soils that are nutritionally adequate, well structured and aerated, and neither waterlogged nor excessively drained, ecosystem recovery from harvesting can be predictable and can occur very rapidly, or at least at acceptable[10] rates. Whether or not the recovery actually does occur at an acceptable rate depends on a variety of biological variables.

Recovery of the biota requires that there be: 1) a residual community of plants, a source of plant seeds or roots/stumps to

---

10 "Acceptable" in this context is obviously defined in social terms, but its precise definition will depend upon which social criteria are used: economic, employment, environmental, etc.

resprout from, or that the plants are re-established as a management activity (eg. planted trees); 2) a residual microbial community or a source of microbial propagules (eg. fungal spores) that can recolonize the soil, and 3) either residual populations of critical soil and other animals, or populations in adjacent areas from which immigrants can recolonize depopulated areas. Rarely, if ever, in managed forests will harvesting alone remove from the entire harvested area all the plants, animals, and microbes that are required for the successional recovery of the biotic community. Erosion, compaction, and/or mass movement of soil (which in total can vary from 0% to up to 50% of a logged area), can cause the loss of living organisms over a proportion of the harvested area, and this will normally result in delayed successional recovery and a significant loss of productivity for some period of time on the affected areas. Such losses are unacceptable and must be prevented whenever possible.

In assessing the long-term impacts of timber harvesting on site productivity as a result of soil damage, it has sometimes been assumed that the damage is permanent; that it will "never" recover. However, to claim that these areas are lost from production in perpetuity is to ignore the processes of successional recovery. Depending on the climate, the surficial and bedrock geology, the size of the seriously-disturbed areas, and the presence or absence of nitrogen-fixing species in the early plant community, recovery of such areas may either be extremely slow or relatively rapid. In most cases, severe and lasting soil degradation is found on only a small percentage of a harvested area apart from roads and landings. The latter can occupy a significant proportion of the harvested area, especially in the interior of B.C.. However, summer skidder or tractor logging in either clearcut or selection-harvested areas, especially on steep slopes, can result in large areas of disturbed soil. Where recovery of disturbed soil is rapid, the rotation-length impacts on growth may be minor, though still unacceptable. Where recovery is slow and the impacts on ecosystem function more prolonged, concern over the damage should be proportionately greater. Major efforts to prevent site damage should be invested where recovery is slow and lost values of various types are high.

The complexity of the issue of ecosystem recovery can be summarized in the concept of "ecological rotations": the time required for a particular ecosystem to recover to its original condition, or some desired new condition following a particular type, intensity, and extent of disturbance. An "ecological rotation" is a measure of the resilience of the ecosystem, and will vary for different climates, different soils, different topographic locations within a climatic area and different components or conditions of the ecosystem. Once the resilience (ie. the ecological rotation time) of a particular ecosystem or ecosystem value has been evaluated, one can determine the maximum degree of ecosystem disturbance that is permissible given a particular frequency of disturbance (ie. the

tree crop rotation length) and a particular desired long-term average condition for that ecosystem. If, for economic or managerial reasons, it is desired to manage this ecosystem on shorter rotations, the maximum amount of disturbance created by harvesting must be reduced.

The concept of the trade-off between the intensity and frequency of disturbance relative to the resilience of the ecosystem is important in the evaluation of the significance of harvesting impacts on the ecosystem. Relatively dramatic disturbance may be acceptable if one plans for very long rotations, or if the ecosystem will recover very rapidly. Very little disturbance is acceptable in ecosystems or specific ecosystem values that are slow in their recovery, or where very short rotations are desired (Figures 2.3 & 2.7).

As a theoretical concept, the idea of ecological rotations may be quite useful, but unless there is a mechanism by which this measure of ecosystem resilience can be established, the concept may not help much in the evaluation of specific cases of harvest impacts; it may remain as a theoretical, academic concept. The complexity of the issue calls for the development and use of ecosystem management simulation models (such as FORCYTE and FORECAST) that can be used to estimate ecological rotations, at least for some aspects and values of the ecosystem. This topic is not dealt with in the main body of the paper, but a discussion of how such simulation models can help in the evaluation of the long-term impacts of harvesting, and the interactive effects between harvest impacts and the impacts of all the other components of a rotation-length silvicultural system can be found in papers presented in Appendix II.

6.5 Closing Statement

Although it is perfectly reasonable, and human, to respond to forest harvesting in terms of its impacts on our senses and emotions, an analysis based solely on emotion-based inputs is unlikely to provide an adequate foundation for regulations and policies that will ensure the conservation of many of the values we are concerned about. The emotional evaluation must be matched by a scientifically-sound analysis of the impacts of harvesting on the components of the forest landscape, and the processes that are responsible for the recovery of the ecosystem from disturbance. This requires a careful analysis of the effects on soils, the microclimate, and the biota: the three major components of a forested ecosystem. It must involve an evaluation of "ecological rotations": the resilience of specific systems to specific disturbance regimes. This in turn requires the use of ecosystem-level management models with which to estimate ecological rotations. Obviously, such a biophysical analysis must be matched by an analysis of the social impacts of different forest harvesting strategies.

SECTION 7. IMPACTS OF FOREST HARVESTING ON SPECIFIC RESOURCE VALUES

So far, this paper has discussed the broad context of forest management within which timber harvesting occurs, the ecological principles that must be considered in evaluating its impacts, the technical and economic considerations that influence the choice of harvesting system, and the impacts of harvesting on the three major functional components of the ecosystem: the soils, the climate and the biota. This chapter briefly reviews some impacts on specific resource values within a particular forest ecosystem. Inevitably, there is some overlap with material presented in earlier chapters, but the redundancy is kept as small as possible. Each of the topics discussed is highly complex, and only a brief introduction to the key issues is attempted.

7.1 The Timber Resource

It has been suggested that harvest-induced damage to forest soils in British Columbia, not including nutrient depletion due to whole tree harvesting, has resulted in a reduction in tree growth that is causing a loss to the provincial economy as large as $80 million per year, and that this rate is increasing by $10 million per year (Utzig and Walmsley 1988). It was estimated by Schwab (1988) that the annual loss of economic activity due to mass wasting[11] in the Queen Charlottes alone could be as high as $3 million a year. Growth losses over a rotation of 80 years on slide areas in the Queen Charlottes were estimated to be as much as 50% (Smith et al 1986). The magnitude of these numbers can be questioned on the basis of the assumptions and data used in the calculations, and these estimates generally ignore the natural processes of ecosystem recovery, but the basic conclusion is sound: that substantial soil damage has been done and continues to be done in some areas of British Columbia by careless or inappropriate harvesting practices, and this has resulted in significant losses in potential site productivity. This does not imply that harvest-induced soil damage is a ubiquitous phenomenon; indeed, many clearcut sites receive so little soil disturbance that they must be slashburned or scarified in order to promote good tree growth. What it does say is that there have in the past been far too many examples of unacceptable soil damage, that damage is still occurring in some cases, and that stricter measures must be put in place to prevent this from occurring in the future.

Losses of tree growth as high as 50% have been reported over three rotations of radiata pine in South Australia due to the combination of soil damage caused by harvesting and site preparation methods, and weed competition (Keeves 1966, Squire *et al*. 1985). The contribution of the actual harvesting activity on its own was not

---

11 Massive soil movements, as in landslides, or the slumping of a slope.

identified but was probably minor. However, a 20% loss of production on a nutrient poor site in Sweden due to whole tree thinning suggests that productivity losses due to nutrient removals in harvested biomass can be considerable on nutrient poor sites (Anderson 1986). Growth reductions of 43% caused by excessive site preparation techniques have been observed recently in 17-year-old radiata pine plantations in New Zealand (Dyck et al. 1989). Again, the main loss in production was attributed to soil damage caused by post-harvest silvicultural activities, not to the harvesting, but there is also increasing concern in New Zealand about potential growth declines due to whole-tree harvesting. These examples are presented to show that loss of site productivity due to forest management has been documented in some areas, that these losses are generally associated with site preparation rather than harvesting per se, but that the practice of whole tree harvesting does pose a risk to long-term site productivity. No long-term field studies of the impacts of harvesting on site productivity have been conducted in B.C. to date, and forest scientists working on this topic generally feel that the risks to long-term site productivity are underestimated by most field foresters.

Losses in the potential of a site to grow trees from rotation to rotation may be masked by the use of "genetically-improved" planted tree seedlings, or by improvements in the composition and structure of the stand. This has occurred in New Zealand where it now appears that the 20% - 30% gain in stem growth that has been achieved due to genetic tree improvement has in some cases masked a substantial decline in soil fertility caused by site preparation techniques.

Stand growth in many young second growth stands in coastal B.C. is apparently exceeding expectations (based on the growth of the previous unmanaged stand). This probably reflects the mobilization of the soil organic matter and nutrient reserves accumulated in the unmanaged forest as well as improved stand stocking. However, computer simulations (using FORCYTE-11: see Appendix II) suggest that such increased production will not be sustained if harvesting, in combination with site preparation techniques, fails to conserve the site's inventory of organic matter, nutrients, and the structure and fertility of the top soil (ie. if rotations are practiced that are shorter than "ecological rotations"). Recent trials in New Zealand showed little difference in growth between genetically-improved and unimproved seedlings when they were grown on badly damaged soil; they both grew very poorly.

In summarizing the impacts of harvesting on the timber resource, there is a strong belief on the part of most professional foresters that, far from reducing forest growth, intensive timber management will increase growth by 50% or more. Use of genetically improved seedlings, maintenance of full stocking, and the use of fertilizers can certainly achieve such increases. However, a number of soil scientists and ecologists believe that unless more attention is

paid to the soil resource(biological as well as chemical), first rotation increases in growth may not be sustained in future rotations. Analyses by forest ecologists also suggest that more attention must be paid to achieving a balance between management-induced ecosystem disturbance and the natural resilience of ecosystems if forest growth is to be sustained.

Experience from around the world is generally encouraging: site-specific, ecologically-sound management results in sustainable or increasing timber yields. However, there are sufficient examples to the contrary to require that more attention is paid to the question of yield sustainability. Ecologically-based computer simulation models should be used to assess these issues until such time that we have gained multiple-rotation field evidence of the long -term impacts of our management. Increased timber yields may be realized at the price of reduced biological diversity, the loss of some species, and perhaps a reduction in the ability of these forests to withstand the stress of global climate change, air pollution, or pathogens. Ecosystem-level analysis of increased yield management scenarios must replace tree population-level analyses if we are to practice sustainable forest management rather than timber mining.

7.2 Wildlife

Wildlife species are very dependent on the habitat conditions created by vegetation. Plants provide food, shelter, habitat, and the environmental diversity required by animals. Different seral stages are characterized by different groups of animal species, and therefore assessments of the impacts of timber harvesting on wildlife can only be made on a species-specific basis.

By increasing the abundance and nutritional quality of herbs and shrubs, clearcutting and other even-aged harvesting systems may increase the abundance of many species of animal, as long as their shelter and security requirements are provided for. Most of the beneficial effects are temporary, of course, because as succession proceeds, early seral communities are replaced by forest. Also, as large areas of unmanaged forest are placed under timber management, wildlife values associated with the old-growth condition will be permanently lost unless a network of sufficiently large old-growth reserves scattered throughout the managed stands is retained, or the specific habitat features required by these species are recreated by management. The retention of "wildlife trees", dead snags, and large rotting logs has been suggested by ecologists in Oregon as one way of retaining these "old-growth habitat structures". Just how much old-growth forest is needed to achieve specific old-growth wildlife management objectives is not yet known for most species, and it is not yet clear as to which biogeoclimatic zones in British Columbia the "new forestry" ideas coming from Oregon apply. Ecological differences between Oregon and British Columbia require a careful analysis to decide in which

biogeoclimatic zones and ecosystem types of British Columbia these ideas and silvicultural systems are ecologically and silviculturally-sound. Undoubtedly they will be very useful and applicable in some areas, but probably not everywhere.

In the early 1970's, wildlife managers, thinking largely about the 'high profile' ungulates (eg. deer and elk), recommended that clearcuts be small and widely dispersed to create a mosaic of stand age classes and to maximize the area of "edge": the interface between clearcuts and the standing forest, which has been shown to be important for these species. Smaller, dispersed clearcuts are also aesthetically more pleasing, at least in the earlier stages of harvesting an older forest. Small dispersed clearcuts may have reduced impacts on fish and water quality, although the increased road building required by this strategy can exacerbate impacts on streams under some conditions, and small dispersed clearcuts increase the risk of wind damage to the remaining stand in areas subject to strong winds. This policy has also resulted in a "fragmentation" of the remaining old-growth into many small patches, and there is growing concern on the part of some "old-growth" ecologists that this threatens certain old-growth-dependent wildlife species(but see the comments below). It has been suggested by these ecologists that a return to larger clearcuts should be considered in some cases in order to retain larger blocks of uncut forest. Just how these two apparently mutually exclusive needs will be balanced is not yet clear.

In general, the trend towards shorter rotations and more open stands (to promote rapid diameter growth) will favour early successional animal species. Where the objectives of management require the maintenance of old-growth-requiring wildlife, silvicultural systems other than even-aged clearcutting will probably have to be used. Where ecologically appropriate, uneven-aged management, two-storied high forest (ie. forest with two distinct age classes and canopy layers), "snag-retention" silviculture, or simply the use of longer rotations may be necessary for those areas in which it is desired to maintain such animal species. There are very few wildlife species in B.C. that are completely dependent on old-growth. Most species found in old-growth forests will adapt to second-growth forests as long as these provide for the food and habitat requirements of the species.

As a final note on wildlife, the problem of road access provided by forest harvesting should be mentioned. Some species, such as grizzly bear, are probably threatened more by over-hunting, poaching, and "nuisance kills" (killing of "problem" bears) than any other factor. The access for poachers and hunters provided by roads, and the increased opportunity for "problems" is probably the greatest threat posed by timber harvesting for such species. The greater length of roading associated with uneven-aged management or dispersed small clearcuts may accelerate the problem in comparison with more conventional clearcutting, at least in the

"first pass" logging. The only way of dealing with this problem would appear to be the creation of rather substantial wildlife reserves (also referred to as wilderness). Recreation in such areas should probably be restricted.

7.3 Fish and Water

As with terrestrial wildlife, fish are very habitat-dependent. Most of the desirable species require cool, clear water, a diversity of stream habitat (alternating pools and riffles), and areas of gravel free of silt and organic matter so that they can spawn. Streamside vegetation is important because it provides bank stability, root wads and bank overhangs (important fish habitat), shade (important for summer water temperature regulation in many streams), "security" and protection from avian predators and an input of insects and leaf litter. Periodic inputs of large tree stems is necessary to maintain stream diversity: many pools are created by such large pieces of organic debris.

Timber harvesting can have negative effects on fish habitat. If logging right to the streambank causes the removal of streambank vegetation and the collapse of bank overhangs, it can result in a significant reduction in the carrying capacity of a stream for fish until these stream characteristics have redeveloped (which they will eventually). Removal of all large trees and snags from the riparian zone will reduce the long-term input of large organic debris to the stream. As the logs that are currently creating diversity in stream habitat decay and are not replaced, stream diversity and fish carrying capacity will be reduced. Removal of streamside shade can cause midsummer water temperature problems in some sections of some streams in areas of the province with high summer temperatures.

Careless harvesting in the vicinity of a stream or river, or debris torrents that move logging slash from summer-dry gulleys into streams during heavy precipitation or snowmelt events, can reduce stream diversity and degrade fish habitat. Such events can result in debris jams that restrict fish movement and can have adverse effects on water chemistry and oxygen content during the summer low water flow periods. They can cause major debris surges that remove all the natural pool-forming debris in the stream and destroy the streambank morphology, both of which are important determinants of fish carrying capacity. On the other hand, logging debris that "bridges" over small streams but does not enter the water can provide temporary shade and stream protection while the surrounding forest is regrowing. Some level of continuing input of organic debris into streams is a necessary part of the normal functioning of a forest stream.

In most cases where streams have significant fish, water and recreation resource values, relatively undisturbed riparian zones should be retained. This may be impossible where there is a

network of very small streams throughout the forest, but it is a sound management objective. Leaving a single row of windfirm trees standing alongside a stream or river generally does not constitute an adequate riparian leave-strip, but in many cases problems of windthrow will make it difficult to retain a more substantial streamside stand of trees unless the strip is rather wide (several tree-heights). In many valleys this would require a substantial portion of the most productive forest land to be reserved as a riparian zone. Only for those streams or sections of streams that have unusually high values (for recreation, or critical spawning areas) will reservation of very wide riparian zones be justified. In some cases, careful removal of the very large trees leaving the understory trees can constitute a satisfactory riparian zone that avoids the problems of windthrow. The recently adopted Coast Fishery/Forestry Guidelines are reported to have resulted in an improvement in the way harvesting affects the stream and fish resource. As in all aspects of forestry, such guidelines must be site and situation specific; they must be flexible and able to deal with the complexity and variability of most field situations. Similar guidelines will be introduced in the interior within the next few years. The negative impact of harvesting on streams that was so common in the 1960's and 1970's appears to have been greatly reduced by the introduction of guidelines, but constant vigilance is needed to minimize such impacts.

Frequently, the major damage done to streams and fish habitat is associated with roads, rather than the harvesting itself. Siltation and landslides caused by roads can have serious negative effects that can vary in duration from temporary (one or two years) to prolonged (many decades). Where harvesting leads to erosion and landslides, and where slash in gullies can become debris torrents, it is the harvesting itself that is the problem. If the risk of such damage from a particular harvesting method is high, alternative harvesting systems should be used. Where the risk is high under any harvesting system and the fish and stream values are high, the forest should probably be designated as "protection forest" and left unharvested.

Water quality has important implications for fish. It also has value in terms of the use of water for drinking, irrigation and for aesthetics. Road and bridge building can result in periods of stream sedimentation especially during high rainfall or snowmelt events. Landslides caused by roads or clearcutting on steep unstable slopes can result in siltation problems. Excessive accumulations of branches and foliage can cause taste problems in drinking water, and the concentration of various nutrients in streamwater, especially nitrogen, may be elevated for one or two years after clearcutting. Such nutrient enrichment caused by harvesting is generally temporary, generally does not pose human health problems, and may increase the fish productivity of nutrient-deficient streams and lakes. Where a lake is already overly enriched (ie. polluted) by sewage, industrial waste, and/or

agricultural activities, even small increases in inputs of nutrients caused by harvesting may be undesirable and unacceptable. Such inputs are generally minor, and detectable stream enrichment immediately downstream of a clearcut normally becomes undetectable in a relatively short distance downstream (100 - 1000 m) due to dilution or the uptake of nutrients by chemical and ecological processes in the stream.

7.4 Range

In most cases, timber harvesting improves range values by increasing the availability of light, moisture and nutrients to herbs and shrubs. Clearcutting in the hottest, driest climates of southern British Columbia is not desirable either silviculturally or from the point of view of range values. As with wildlife, sheep and cattle in such ecosystems require access to shade during the heat of the summer, and protection from wind-chill in colder seasons. Other silvicultural systems should be used in such forests, and increasingly they are. Generally, there are few conflicts between harvesting and range, and where conflicts occur (eg. trampling or browsing of seedlings), they can usually be solved by careful management of the grazing animals. In several parts of the interior, clearcutting followed by grass seeding is a satisfactory way of providing rotational grazing at the start of each tree crop rotation (eg. lodgepole pine forests in the Cariboo). However, excessive competition for soil moisture between young trees and grasses will occur if the grass is permitted to become too vigorous and abundant, and this can severely impede early tree growth.

7.5 Recreation

Of all the issues currently faced by foresters, it is the conflict between timber harvesting and recreation that is the most contentious. Although many of the legal battles being waged between environmentalists and the forestry profession in the U.S. Pacific Northwest are over wildlife habitat for "rare and endangered species" (eg. the spotted owl issue), this is as much a consequence of the nature of U.S. legislation as it is a concern about the animal species. Although there is certainly concern about conserving species where their survival is threatened, and rightly so, in many cases legislation to protect rare and endangered species is being used to prevent areas of old growth that are valued largely for their aesthetic, spiritual, and wilderness recreational significance from being harvested.

There can be little doubt that the recreational significance of the forests of British Columbia is increasing and that the aesthetic and recreational implications of timber harvesting should have been a major management consideration at least a couple of decades ago. Had this occurred, some of the current conflicts might have been avoided. Much of the most spectacular scenery and recreationally-

significant forest land in this scenically spectacular province is already protected in parks, but there are also large areas of world-class scenery in areas dedicated to timber management. Further protection of the visual resources of the province for purposes of recreation will undoubtedly occur, and this should be accounted for in provincial-level forest planning. Almost certainly the provincial and national parks systems in British Columbia will be expanded, and this will remove areas of forest previously dedicated to timber production. In addition, the pressure to preserve existing visual values in timber-production forests will create significant conflicts with timber management as the second and then the third rotation tree crops are harvested. Visual corridors will have to be established in areas that have high recreational significance, and harvesting patterns in these corridors modified according to the dictates of recreation needs, landscape architecture, and visual resource management.

It is probable that there will be an increase in the reservation of old growth forests for recreational purposes, but in most cases this does not imply the setting-aside of vast areas. The conservation of representative examples of various types of old-growth for recreational purposes is a separate issue from the creation of "wilderness"; different sized reserves are required for these different types of land use. "Pocket wilderness" old growth patches should be reserved in each major valley system in which such forest still exists, and the forest around these reserves should be managed under longer rotations and with modified harvesting and silvicultural practices. Failure to do this will undoubtedly sustain the current polarized battle to save every unroaded major valley in its entirety.

Many of the widely publicized concerns in the media about the "environmental destruction" caused by timber harvesting appear to be more related to the aesthetic impacts of harvesting and the emotional effect this has on people than it does with unacceptable alterations in site ecology and the ecological processes of ecosystem recovery. This is not to say that unacceptable ecological changes are never caused by harvesting, but that the public's perception of harvesting is based more on short-term visual assessments than on a scientific evaluations of the changes in ecosystem structure and function. Greater sensitivity to aesthetics and recreational values may defuse many, though not all, of the current forestry-environment conflicts. However, care must be taken that in making forestry look nice, questions such as long-term site productivity and biotic diversity are also addressed. "Ecologically-sound" forestry can sometimes look much less attractive than forestry designed specifically to look nice, but which ignores the long-term functioning of the ecosystem.

7.6 Wilderness

The term "wilderness" means different things to different people,

but the essence of the term is an area that is "natural" in the sense of being unaltered by human activity: an area in which the prevailing ecological processes determined by climate, topography, soils and the native living organisms operate unaltered by human technology. As it is used today, wilderness can mean a wildlife reserve, an area for certain types of recreation, or an area that gives pleasure to people simply because they know it exists. Wilderness is different from ecological reserves and old-growth reserves, although a single reserve can fulfil all these functions. In many cases, wilderness conflicts are about recreation issues. In others they are about old-growth, wildlife, or "bio-diversity". In all cases, they are a question of land use. They should be dealt with according to which of these issues is the basis for the land-use conflict.

Management for wilderness is as valid a part of forest land management as timber management, if the maintenance of wilderness values is one of the objectives of management. That it has not been an objective of forest management in British Columbia is one of the reasons for conflicts between foresters and wilderness preservation groups. In most cases wilderness is incompatible with many other land uses. Roads, timber management, wildlife management, hunting with guns, trapping, livestock grazing, and mining are not compatible with true wilderness. Fishing is usually considered to be compatible. Low levels of hunting and trapping using low-technology, "traditional" methods may sometimes be acceptable, as long as the harvest is only taking excess animals that would leave the area or die anyway. Timber harvesting is normally considered to be incompatible, although it is the associated roads and the consequent access by vehicles that is often the major problem. Occasional helicopter logging using the selective system can be compatible with some aspects of "wilderness recreation".

Most of the designated wilderness in British Columbia is managed by the Ministry of Parks, not by the Ministry of Forests. Many of the conflicts between wilderness and forestry in this province result from the failure of the public to understand that large areas of public forest not in parks have been part of the timber production land base for many decades and that these areas are destined to be harvested. The high standard of living in British Columbia has to a considerable extent been possible because these areas were dedicated to timber production.

7.7 Conclusions

Timber harvesting can result, and often has resulted, in negative impacts on a variety of forest resource values in British Columbia. Almost no generalizations that are true for the entire province are possible. For almost every case of a negative impact of a harvesting practice, it is possible to find a positive outcome for a similar practice elsewhere. Exceptions include massive soil

erosion, slope failures and soil compaction; debris avalanches in streams; and major visual alterations to the landscape by large scale clearcutting in steep mountainous country. Their impacts are almost always negative. However, the damage is not "forever". Forest ecosystems have in the past, and will in the future, recover from all but the most extreme disturbance events, and the "damage" from even these will eventually be "repaired". The question is not "will the ecosystem recover?", but "how long will it take?". Thus, the debate about the impacts of forest harvesting on other resource values should shift from a pre-occupation with "how much damage has been done?" to include consideration of "have the mechanisms of ecosystem recovery been damaged?", "how soon will lost values be restored?", and "how long should the ecosystem remain undisturbed before it is able once again to sustain and recover from the subsequent disturbance?".

Much of the discussion in this chapter has dealt with impacts of timber harvesting on the resource values of a particular forest ecosystem. Many of the conflicts transcend this local level. Even if site-level timber harvesting is exemplary, a variety of problems can be created if the rate of harvesting of the entire forest is too high, if it causes age-class distribution problems, or if the spatial distribution of harvested areas in the landscape conflicts with other forest-based resource values. These important "forest-level" aspects of timber harvesting were given brief mention in Chapter 3, but deserve as much scrutiny by the Commission as the local site issues examined in this paper.

CHAPTER 8. HARVESTING AND THE OLD-GROWTH ISSUE

Saving old-growth forests had become a major issue for the environmental movement in British Columbia by the mid 1970's, and it became their major focus in the 1980's. Although this paper is mainly concerned about the impacts of timber harvesting, the question of old growth does need to be addressed, albeit briefly.

One of the major problems with the old-growth issue is the difficulty of defining what "old-growth" is (see Appendix III). This is not so much a problem of devising an ecological definition, although different definitions are needed for many of the different types of forest that we have in British Columbia. The main problem comes from the wide range of values that the public associates with what they think of as old-growth. These values include one or more of: tree age, tree height, tree diameter, forest stand structure, species composition, the presence of large standing dead trees and large decaying logs, and whether or not the forest is a true successional climax. Where there is an old climax forest, that is what people may think of as old-growth. In a region where all climax forest has been removed by natural disturbance or logging and there is only natural second growth, managed forest, or previously harvested forest, the largest, oldest stands will be what many people will regard as old-growth (for example, Stanley Park and Pacific Spirit Park (previously the U.B.C. Endowment Lands) in Vancouver). Sometimes the old large trees that people value are self-replacing climax forest. Sometimes forests of giant trees are actually early or mid-seral stages that in due course of time are replaced by a more diminutive type of forest (eg. the giant eucalypt forests of the humid parts of Tasmania, Australia which are of fire origin and are replaced in the absence of fire or forest harvesting by relatively diminutive temperate rain forest or Nothofagus (southern beech) forest).

Clearcut harvesting with short rotation, even-aged management is incompatible with the maintenance of a variety of "old-growth values". However, maintenance or renewal of the old-growth characteristics mentioned above should be well within the technical possibilities of forest management in many areas. Intensive silviculture can also produce exceptionally large trees in a remarkably short period of time. Uneven-aged silvicultural systems, harvest systems that retain large standing dead trees and large rotting logs, and the use of longer rotations may be less economically efficient and pose many more technical problems than shorter rotation, even-age silviculture with clearcut harvesting, but these management techniques can sometimes make it possible to maintain timber production and a variety of old-growth values in the same area. Where the public demands the sustained provision of old-growth values in a timber production forest, the use of alternative approaches to silviculture and management should be considered, as long as this does not have an unacceptable impact on other forest resource values.

The old-growth question is currently the subject of a Ministry of Forests "strategy" project. Committees are examining a wide range of old-growth issues, from definition, to inventory, to research needs. One could anticipate that the strategy that will result will involve a variety of definitions of old-growth, possibly one for each of the major forested biogeoclimatic zones in the province. The strategy will probably suggest the creation of additional old-growth ecological reserves and reserves to satisfy recreational needs. The latter should be based on a management zoning approach that nominates candidate areas relative to the geographical distribution of society's needs for old-growth-based recreation.

Whether or not existing old-growth forests will survive the predicted global climate change, and how such a climate change would affect our ability to conserve or recreate old-growth values, is not know. If the massive climate change that is predicted does occur, many of our old-growth reserves may change substantially or be lost entirely. This should be considered in creating an old-growth strategy for the province. It may become necessary in the future to establish new forests with the specific objective of managing them to become future old-growth reserves.

CHAPTER 9. HARVESTING AND CLIMATE CHANGE

Most of the concerns about the impacts of timber harvesting in the past have addressed issues of site productivity, reforestation, soil damage, wildlife, fish and water, aesthetics, wilderness and recreation. These are valid concerns, but they are rapidly becoming overshadowed by the spectre of global climate change. It is argued, and widely accepted, that anthropogenically-induced changes in the concentration of "greenhouse" gases[12] in the atmosphere are altering the global radiation balance and leading to global warming. There is as yet no statistically-sound climatic evidence that global warming has in fact begun. Normal climatic variations associated with El Nino, La Nina, and a variety of other known climatic cycles make it difficult to reach conclusions from short-term trends. Most predictions about future climate change have not dealt adequately wit the very complex role of clouds in the global radiation balance, and this renders all existing predictions very speculative. Consequently, there is still much uncertainty about the "greenhouse effect". These concerns notwithstanding, the majority of atmospheric scientists and ecologists believe that it will occur, that it is probably occurring already, and that the ecological consequences could be so great as to overwhelm most other current environmental concerns.

On a geological time scale, the "greenhouse effect" is probably postponing the onset of the next glacial period. However, with time scales in the tens of thousands of years, this "temporary" benefit[13] is insignificant compared with the ecological and social disruption that will attend the anticipated rates of directional change in global climate: rates that are believed to be unprecedented over the past million years, and perhaps over the past sixty million years. All aspects of human activity must be scrutinized to establish the extent to which they are part of the "greenhouse problem" or part of a potential solution.

The forests of the world, which until about 100 years ago covered much of the earth's land surface, have certainly played an important role in the regulation of atmospheric chemistry in the past. Much of the world's great fossil fuel deposits represent the storage of carbon originally taken out of the atmosphere by forest

---

12 Greenhouse gases such as carbon dioxide, methane, ozone, chlorofluorocarbons and others, have the property of being transparent to "light" wave lengths but opaque to infra-red wave lengths of radiant solar energy. Such gases in the atmosphere act like the glass of a greenhouse, trapping solar energy and causing an increase in the temperature of the atmosphere.

13 The "greenhouse effect" will probably end when we run out of fossil fuel unless by that time we have inadvertently set in motion processes such as the melting of permafrost and ice caps that could continue to escalate the problem after the human contribution to atmospheric chemistry change has been terminated.

photosynthesis. However, over geological time scales the role of forests as a long-term carbon "sink" is generally believed to have been less important than that of the oceans, which have removed vast quantities of carbon and deposited them as chalk, limestone, coral and fossils fuels on the ocean floor. These are the great carbon deposits of the earth., not forest-derived peat, coal, and soil organic matter. Forests do store carbon, but once most forests reach maturity, their inventory of carbon becomes fairly constant. In bog forests, cold northern forests, and some cool temperate rain forests, there may be a slow, long-term accumulation of soil carbon between successive glacial periods, but in most forests much of the stored carbon is released back to the atmosphere periodically by fire, insects, diseases or wind disturbance. There continues to be great uncertainty concerning the short and medium-term roles of forests and oceans, and recently it has been suggested that the northern boreal forest is increasing its storage of carbon. This could be due to accelerated tree growth in response to increased atmospheric CO_2 concentrations and higher summer soil temperatures. Unfortunately, we do not have reliable quantitive estimates for most of these conditions and processes. Much more research is needed before we can draw firm conclusions on these issues.

The area of forest around the world has been seriously reduced over the past few centuries, and large quantities of carbon dioxide (CO_2) have been released to the atmosphere in the process. Nevertheless, sufficient area of forest is left for the contribution of the management of these forests to the global carbon budget to be one of the factors to be considered in evaluating the "greenhouse problem". In particular, how does the effect of converting old-growth or previously unmanaged younger forests to young managed forests affect atmospheric CO_2 concentrations?

As was described in earlier sections, timber harvesting is followed by a considerable loss of carbon-rich soil organic matter, with or without slashburning, as a result of post-harvest microbial activity. Much of this carbon is released to the atmosphere. Where the harvested stems are used to make disposable paper, which is subsequently burned or decomposes in a landfill, much of the harvested carbon is also returned to the atmosphere. If the decomposition in these landfills is anaerobic (which it usually is), the carbon will be released as methane rather than CO_2, methane being a much more potent greenhouse gas than CO_2 (twenty-five times more effective according to one source). Alternatively, where the harvested trees are manufactured into wood which is used in long-lived buildings, the harvested carbon is kept out of circulation.

If a productive new forest is established following the harvest of a mature or old-growth forest, much of the carbon released from the soil and forest floor of the old growth may be recaptured within

a few decades, or at least over the first rotation. For example, the forest floor of a 450-year-old forest in Oregon was reported to have 170 tons of carbon per hectare in comparison with 433 tons in the trees (Harmon et al. Science, Feb. 9, 1990). The trees in a sixty-year-old plantation were reported to contain 187 tons. If all the old-growth forest floor were lost after harvesting (extremely unlikely), apparently the losses would be recovered by the trees in the first rotation. It would take much longer to recover the carbon in the harvested old-growth boles if these were manufactured into short-lived products that rapidly returned the carbon to the atmosphere, rather than into long-lived timber products. These authors estimated that it would take 200 years of new forest growth for the total ecosystem carbon storage to approach that of the old-growth forest. They estimated that sixty-year-old plantations only contain about 50% as much carbon as the 450-year-old old-growth.

Successive crops of trees that are harvested for lumber can represent a carbon sink in comparison to the relatively static inventory of carbon in an old-growth forest. The number of rotations of managed tree crops that must be harvested before the carbon release from the old-growth stand is compensated for will depend upon how much carbon is lost from the old-growth and the rate of growth of the managed forests, both of which will vary from site to site within a particular type of forest. It will also vary considerably between the different biogeoclimatic zones and subzones in British Columbia. The analysis from Oregon cited above is valid for the coastal Oregon forests from which the data was obtained. Similar analyses should be conducted for all the major types of forests in British Columbia. It is anticipated that this would reveal wide differences in the effects on the carbon budget of converting unmanaged forest into managed forest. The Oregon data are from a forest with biomass and stored carbon values that are far higher than in most of the forests of British Columbia. The warmer climate of Oregon would be expected to result in a more rapid loss of forest floor and soil organic matter following timber harvesting than in the cooler climates that characterize most of British Columbia.

The forest floors and mineral soils of managed forests rarely contain as much carbon as old-growth forest floors and mineral soils, so a significant amount of carbon must be invested in long-lived wooden structures using lumber from managed stands before the reduction in soil carbon is compensated for. If old-growth trees are used for pulp rather than lumber, there will be a considerable net release of carbon from the forest to the atmosphere following the conversion of old-growth forests to managed plantations, the extent of the release depending on the type of forest. However, the net release of carbon by converting old-growth to managed forest is considered to be small compared to the global fossil fuel release of CO_2 (Harmon et al.'s 1990 estimate of the annual release of carbon from converting coastal Oregon and Washington old-growth

to second growth is equal to about 0.3% of the annual global fossil fuel release), and CO_2 is considered to be only half of the overall greenhouse problem. Methane, nitrous oxide, chlorofluorocarbons, and other gases make up the other half of the annual contribution of greenhouse gases to the atmosphere by human activity. This comment does not in any way reduce the concern we should have about the release of carbon to the atmosphere by timber harvesting, but serves to put loss estimates in perspective.

It has been estimated that if all of the areas of the world that have been converted to agriculture and other non-forest land uses over the past two centuries could be instantly reforested, and tree growth sustained at levels approaching those of subtropical plantations (most of the deforestation has occurred in the tropics), about five billion tons of carbon would be removed from the atmosphere annually. This is close to the roughly six billion tons of fossil fuel carbon released annually. However, unless these trees were harvested, this removal would only occur for about twenty years (the time in which tropical plantations approach maximum biomass). If, when they were harvested, they were used for pulp, much of the carbon would soon be returned to the atmosphere. If they were used for lumber, the carbon would remain stored for a longer period. The fact that politically, economically and socially, such massive and instantaneous reforestation could not happen reduces this idea to merely an example that puts in perspective the importance of the role of forests in the global carbon cycle. The idea that we should reforest denuded land whenever possible has great merit with respect to the global climate change issue, but it should be remembered that this would displace many non-forest plant communities and their associated animals, and would have impacts on the visual qualities of the reforested landscape. Sometimes these effects would be welcomed by the public, and sometimes they would be rejected.

The conclusions that can be drawn about forest harvesting and the "greenhouse effect" is that it is important to maximize the rate at which forests accumulate organic matter, and minimize the loss of organic matter from forests. A good strategy from the perspective of global climate is thus a good strategy in terms of long-term site productivity and the sustainability of forestry. However, if the harvested materials are used by our profligate society as throw-away products, the overall long-term contribution of productive forest management to solving the "greenhouse problem" will be minor, and may even be negative. In general, the net contribution of CO_2 to the atmosphere caused by the conversion of organically-rich coastal old-growth forest to managed plantations is small relative to other sources of greenhouse gasses and is a correspondingly small part of the overall global climate change problem.

CHAPTER 10. THE CLEARCUTTING ISSUE IN BRITISH COLUMBIA

10.1 Timber Harvesting Around the World

Because so much of the public concern over timber harvesting is actually concern over clearcutting, this chapter attempts to synthesize several of the points made in earlier chapters. It presents a summary statement about the practice of clearcutting. Inevitably, there is some overlap with earlier discussions.

The use of clearcutting as a timber harvesting system has had a long history and is currently the most commonly used method around the world. It is ecologically the most appropriate system for species that are light demanding in their regeneration phase, and in climates or on sites in which light competition is a factor that limits regeneration. Species like pines and eucalypts require close to full light for optimum regeneration in humid climates or on moist sites, and species like Douglas-fir regenerate best in clearcuts, except in the hottest and driest parts of their range. Clearcutting is also ecologically appropriate for species that are adapted to the ecological conditions found in large openings in the forest created by wildfire, large-scale windthrow, and epidemic insect or disease outbreaks. This statement says nothing about the size of clearcuts. In many cases clearcut patches have been much larger than is necessary to create the microclimatic conditions needed by light-demanding species, and in some cases excessive size of clearcuts is a problem for regeneration, wildlife and various other values. However, the question of the size of a clearcut area is a different issue from whether or not clearcutting is the appropriate harvesting system.

Uneven-aged management is practised in a variety of countries and also in various parts of British Columbia. It is usually restricted to forests of shade-tolerant tree species, or to sites or climates in which tree species normally thought of as light demanding are shade tolerant or even shade-requiring (hot, dry sites in hot, dry climates). Individual tree selection, or more commonly group selection, is used as a harvesting method in protection forests in Europe to maintain continuous forest cover on unstable slopes or where there is a risk of snow avalanche or cold air drainage. Group selection or very small patch cut harvesting is used in some European subalpine forests to promote advanced regeneration or natural regeneration following harvest. Individual tree selection is sometimes used in forests of extremely shade tolerant European beech on very fertile moist sites in France to obtain natural regeneration without weed problems. It may be done in some areas to maintain wildlife winter range, or in areas of high recreational value. Helicopter logging in uneven-aged forests may leave the forest with the appearance of being unharvested.

The current public preoccupation with the perceived evils of

clearcutting are not new. Historical records show that regulations restricting clearcutting were introduced in Germany many centuries ago as a result of problems associated with this harvesting practice when applied in steep, mountainous country. Similar restrictions in southern Europe apply to steep slopes of the Alps, especially in areas of highly erodible limestone or avalanche danger. However, clearcutting is widely used today in Germany and other European countries for those species and on those landscape units where it is appropriate, albeit with much smaller sizes of clearcut than have been common in British Columbian forestry.

Experience with uneven-aged silviculture in Scandinavia over the first half of this century was not very satisfactory. The cold northern boreal forest appears to be best suited to even-aged management with clearcut harvesting. The development of cold soils, an acidic, slowly-decomposing forest floor, and dominantly ericaceous vegetation or thick moss layers can lead to reduced soil fertility and stand growth in these northern forests. The ecosystem disturbance of clearcutting, often followed by slashburning or mechanical site disturbance, appears to accelerate the rate of many ecosystem processes and to improve site productivity as long as the disturbance is not excessive. Examples have been documented in which severe mechanical and slashburning site preparation treatments on nutrient poor sites following clearcutting in Sweden have led to significant loss of productivity. These declines were not caused by the clearcutting, however, and only occurred on poor sites. Natural unmanaged boreal forests in Alaska and northern Canada also exhibit a marked tendency to stagnation, permafrost and muskeg formation unless periodically disturbed, usually by wildfire. Periodic disturbance appears to be necessary to maintain these forest ecosystems in the productive stages of their successional sequence. The climax condition may be a bog, not a forest.

In contrast to these examples where even-aged management is believed to be superior to uneven-aged management, there are plenty of examples where clearcutting has proven to be inappropriate. These range from hot, dry sites in California, Washington, Oregon and southern B.C., to some subalpine forests, to tropical rain forests on poor soils. There is little doubt that there is need for some expansion of the use of uneven-aged systems in British Columbia, but it should be remembered that many of the negative consequences associated with clearcutting have actually been the consequence of inappropriate post-harvesting site preparation treatments, or excessively large clearcuts, rather than clearcutting *per se*.

In Chapter 1, it was noted that the history of forestry in various different countries has almost always involved the transition from administrative, non-ecological forest management to an ecologically-based silvicultural strategy because of the failure of the former approach. As society becomes more aware of the

urgent need to manage our environment wisely, there is a danger that the mistakes of the early stages of forestry will be repeated in the early stages of conservation: that in trying to ensure a sustained supply of certain forest resources the public will seek to have blanket regulations introduced that require the universal banning of one practice, and the ubiquitous application of another, irrespective of the local site ecology and other considerations. Timber harvesting practices in many parts of the world certainly require improvement, and a significant change is needed in the level of sensitivity on the part of foresters, and especially timber harvesters, to the variety of resource values that can be negatively affected by timber harvesting. However, the changes made in the name of conservation must be ecologically sound, and must be based on a clear understanding of the rotation-length and multi-rotation consequences of alternative harvesting and management strategies for all the resource values of concern. The changes also require a clear definition of the objectives of management by the landowner. Foresters work to achieve clearly stated and achievable goals. In British Columbia, the goal was, until quite recently, to maximize the economic return from timber management, and the forest management that has been practised, including clearcutting, has reflected this objective. The B.C. government must provide forest industry with clear management goals, performance standards, and operational guidelines concerning how the forested landscape is to be managed. When ecologically-sound and site-specific goals and regulations are in place, foresters can be held accountable for the achievement of these goals.

10.2 Clearcutting in British Columbia

There are few environment-related issues in British Columbia today that transcend the clearcutting issue. It is intimately related in the minds of many of the public with issues of global climate change, old-growth, and loss of biological diversity. There appears to be a widespread belief, based on statements by some environmentalists, that clearcutting "destroys ecosystems". Unfortunately, most of the public pronouncements on clearcutting lack a sound foundation of scientific evidence and do not reflect our current understanding of the ecology of our forest ecosystems. There is sometimes confusion in the minds of the public between the environmental effects of clearcutting and the effects of post-harvest site preparation (eg. slashburning), and with the forest management issue of over-cutting. Whether or not the forests of B.C. are being logged too quickly has little to do with whether or not clearcutting is a silviculturally and environmentally sound practice.

British Columbia has an exceptionally high diversity of physical environments as a result of its high climatic, topographic, geological and soils diversity, its large latitudinal range, and its longitudinal range from coastal to continental environments.

This physical diversity is reflected in a high geographical diversity of fauna and flora, although the species diversity of individual local ecosystems is often quite low relative to forests at lower latitudes. This low species diversity on a particular site is believed to reflect the short period of time since B.C. was glaciated.

Accompanying the physical diversity of the province, there is a large diversity of forest ecosystem types, with different species, stand structure, sensitivity to disturbance, patterns and rates of successional recovery, and non-timber resource values. The only successful basis for renewable resource management in this highly varied landscape is site- and species-specific ecologically-based management prescriptions. These must reflect management objectives that are sensitive to the local ecological conditions, which in turn set the ecosystem potential and constraints on management. Many of the past failures of forestry in British Columbia and the rest of Canada have been largely the result of applying a single set of silvicultural strategies and management approaches across an ecologically variable landscape. Inevitably, forest management applied in such an ecologically-insensitive manner works well in some places, is mediocre in others, and is a total failure in yet other locations.

History has a habit of repeating itself. The current public antipathy towards clearcutting is generating pressure to ban clearcutting and replace it with alternative harvesting strategies. Although it is true that clearcutting does not duplicate exactly the large-scale environmental disturbance caused by wildfire or windthrow, the ecological differences between clearcutting and these natural disturbances are generally sufficiently small that species adapted to such natural disturbance are also well adapted to the clearcut environment. An exception to this might be hot, dry environments in which the shade cast by standing dead trees following a fire plays an important role in protecting young seedlings from excessive heat and light. Another exception would be whole-tree harvesting on sites where logging slash (rotting wood and tree crowns) plays a critical ecological role. Yet another exception would be where the frequency of management-related disturbance is much different from the frequency of natural disturbance. However, even in these three exceptions, the pioneer tree and other plant species that would invade a burned or windthrown forest on such sites would generally be reasonably well adapted to the clearcut environment.

There are certainly too many examples in British Columbia where clearcutting has led to soil erosion, wildlife habitat damage, stream damage, aesthetic damage, delayed forest regeneration, and reduced site productivity. However, there are large areas of forests that have developed following clearcutting that would be judged by international standards to be examples of excellent silviculture that is compatible with many other forest resource

values. Where the size, orientation and method of clearcutting have been sensitive to the ecology of the area and the crop species, and to non-timber resource values, clearcutting has been shown to be silviculturally-sound and compatible with these other values.

There have been relatively few attempts to try alternatives to clearcutting in British Columbia. There are many areas in the hot, dry southern interior where non-clearcut harvesting methods would be more appropriate than clearcutting for a variety of reasons, and there are undoubtedly other areas in the province where shelterwood or other non-clearcut even-aged systems could be used to advantage. Some reasons for the antipathy of B.C. foresters towards these other harvesting methods include the virtual impossibility of conducting selection logging or other uneven-aged systems in west-coast old-growth "rain forest" without damaging the residual trees, the failure of a few early experiments in the interior with some classical European harvesting systems, and the very negative effects of poorly-regulated <u>selective</u> logging ("diameter-limit cutting" and "high-grading") in some parts of the interior. As has always been the case in European silviculture, wind sometimes dictates the manner in which forests are harvested, and wind has caused the failure of many experiments with alternatives to clearcutting old-growth or unmanaged younger forests.

Undoubtedly these early failures were over-generalized, and they may sometimes have been used as an excuse to clearcut in forests where other harvesting systems would have been better. However, there is also little doubt that clearcutting, albeit with smaller and dispersed openings where appropriate, is the most effective, safe and ecologically-sound way to harvest most of the remaining old-growth coastal forests. The same is true for many of the interior mature and old-growth forests. Although other systems may well prove to be practical, and even superior,in some future second-growth stands, it is often impossible to use harvesting methods that work well in highly cultured, managed forests in the harvesting of old-growth forests. In the case of large areas of insect-killed single species forests in the interior (eg. pine or spruce), there is generally little alternative to clearcutting. Where only one of several species has been killed, salvage logging can create or maintain uneven-aged stands.

The confusion between clearcutting and over-harvesting is unfortunate. It is argued convincingly by many that the current rate of forest harvesting is not sustainable given the current level of forest management. Where this is proven to be the case, the rate of harvesting should be reduced to a sustainable level, subject to a rational level of flexibility in the actual annual cut. Whether or not the annual allowable cut is achieved by clearcutting or some other method of harvest is a completely separate question.

The issue of overcutting is very important not only because of the implications for future jobs and provincial revenues, but also because it can create future age-class distribution problems in our forests (see Chapter 3). The age-class distribution and the spatial arrangement of different age-classes across the landscape have important implications for wildlife habitat, and also for range and recreation values. They can have significant effects on water and fish resources.

10.3 Predicting the Long-term Consequences of Alternative Forest Harvesting Strategies

One of the difficulties in making choices between different ways of managing and harvesting British Columbia's great diversity of forests is the lack of rotation-length experience of the outcomes of the different management strategies. The forest growth and yield prediction tools used by foresters are mostly a simple or sophisticated projection of past patterns of growth into the future. Lacking evidence of past growth under a variety of different harvesting patterns, these growth and yield prediction tools cannot give us a "crystal ball" to foresee how our forests would respond to different harvesting and other management practices. Nor can they predict future forest growth under altered climatic conditions.

In many parts of Europe and Scandinavia, there is several rotations-worth of experience concerning the response of forests to various management strategies. In the absence of such experience in British Columbia, there is a need to use this overseas experience, where it is ecologically, socially, and silviculturally appropriate. There is also a need to use ecosystem management simulation models such as FORCYTE (FORest nutrient Cycling and Yield Trend Evaluator) or FORECAST (FORestry and Environmental Change ASsessmenT). Until we have gained our own rotation-length experience, models of this type can be used to produce the best currently available scientifically-educated "guess" as to probable future trends in forest growth under different management and harvesting regimes (see Appendix II), and under possible future climatic regimes. At least they should be able to provide us with a ranking of the potential outcomes of different ways of managing our forests.

The Bureau of Land Management in Oregon, faced with a public challenge to the believability of their conventional growth and yield prediction models, have been using FORCYTE, and there is a growing interest amongst the Forest Growth and Yield Cooperative of the Pacific Northwest in developing/using such models as an adjunct to their traditional yield predictors. It is time that this third generation type of growth and yield model is utilized to help predict how various different forest types will respond to various alternative management strategies.

CHAPTER 11. IMPACTS OF HARVESTING ON THE NATIVE PEOPLES OF BRITISH COLUMBIA

This paper was not intended to address the native land claims issue, and will not do so. Comments with respect to the native peoples of the province are restricted to the actual and potential impacts of forest harvesting on this sector of B.C. society.

Timber harvesting has several actual or potential impacts on the native peoples of the province. By providing employment in rural and remote areas, timber harvesting and the associated transportation, manufacturing and silvicultural activities can make an important social contribution. Where native peoples have been successful in obtaining and operating cutting rights on forest land tenures, they have been able to develop community-based forest industrial activities. These have contributed employment and a significant financial input to the community. It is anticipated that the contribution of the native peoples to the management of the province's forests will increase, and that timber harvesting will become a significant economic base for many of the native communities in the province.

Where timber harvesting increases populations of game animals, this will be a benefit to those native communities that utilize these game species for food, employment and income. Similarly, where harvesting has a negative impact on wildlife (eg. fur-bearing species that are dependent on old-growth or mature forest), there will be a negative impact on native communities that are dependent on trapping these animals. Forest access provided by logging roads may increase both legal and illegal hunting pressure on wildlife, with negative consequences for native communities that utilize the wildlife resource. Negative effects on fish and water will have a negative effect on native users of these resources.

The native peoples of British Columbia have traditionally enjoyed the spiritual values of the forest. Certain forest areas have particular historical and spiritual importance, and timber harvesting may have negative effects on these values. For some members of the native peoples, these historical and spiritual attributes of the forest will be of equal or greater value than the material values.

The impact of land use on the native peoples of British Columbia has not been given adequate attention in the past. Consideration of this issue should be one of the several factors that determines if, how, and when timber harvesting takes place.

CHAPTER 12. SUMMARY AND RECOMMENDATIONS

It is difficult to summarize the diversity of issues covered by this paper in a few brief statements. However, the following points capture the main ideas presented in the body of the paper.

a. An examination of the development of forestry in British Columbia over the past century shows many parallels with comparable forest histories elsewhere in the world. This suggests that we can learn from the history of countries that are already at a more advanced stage in the evolution of the use of their forested landscapes. The major lessons to be learned are that: 1. forestry must become sustainable in terms of the values desired by society from the forest; 2. in the case of publicly-owned forests (as in British Columbia), the government must develop a clear set of objectives, policies and performance standards under which industrial forestry enterprises can operate. Without the appropriate policies in place, it is unlikely that the forest management that is practised will satisfy the prevailing desires of society for their forest-based resources; 3. foresters must become more sensitive to the attitudes of society towards forestry and the environment. They must also be more open to input from local communities concerning how the forests should be managed; 4. regulations designed to improve the quality of forest management and to protect the environment must be ecologically sound. They must be sensitive to the emotional impact of forestry practices on the public, but there must be a balance between what is socially, economically and ecologically-sound, and public responses based largely on this emotional impact; and 5. unless foresters and forest scientists invest more effort in communicating to the public the available knowledge about how forest ecosystems function and respond to disturbance, and the objectives and methods of management, forestry will be controlled more by political than by technical and scientific criteria. In many cases, political control will not improve, and may well impair, the degree to which society's demands on the forested landscape are satisfied over the long-term.

b. Forest harvesting decisions in British Columbia in the past have generally been based more on technical and economic criteria than on silvicultural and ecological criteria. As in most forests of the world, there has been a persistent failure by forest harvesters to understand, consider, and respect the soil component of the forest ecosystem. Significant and unacceptable damage has been, and sometimes continues to be done to soils, and long-term site productivity has been impaired in some areas. Although silviculture in British Columbia has recently been placed on a sound ecological footing (it must be practised on the basis of the biogeoclimatic ecological site classification system and a Pre-harvest Silvicultural Prescription based on this system, must be done before any logging is permitted), this does not yet appear to be adequately reflected in the way forest harvesting is being

conducted in some areas, although improvements have been made. Much more effort is needed to educate forest harvesters about soils, and about the impacts of harvesting activities on a wide variety of resource values. The planning role of the professional forester should be strengthened to include a greater influence over the harvesting phase of the silvicultural cycle.

c. Many of the "environmental" problems covered by forest harvesting are related to roads and the aesthetic impacts of clearcutting. Stricter controls should be exercised over the location, design, drainage, construction and maintenance of permanent roads. Temporary roads, skid trails, and landings should be rehabilitated to prevent erosion, and the disturbed area returned to a productive condition. More attention should be paid to the aesthetics of clearcutting, in terms of the size, shape, orientation, and location of the openings, as well as to the ecological impacts.

d. Because forestry in British Columbia began with harvesting of unmanaged forests, harvesting became "the tail that wags the dog". In countries where tree crops have been grown from an initial non-forested condition, harvesting is simply the final silvicultural activity in the crop production cycle. As British Columbia moves from old-growth harvesting to the management of second growth forests, timber harvesting must take its appropriate place in the overall forest management scheme. Once this is done, it will be much easier to apply guidelines that will limit the negative impacts of harvesting on the variety of resource values provided by forests.

e. The current preoccupation of the environmental movement with old-growth forests requires that silvicultural systems be implemented that can sustain or re-create a variety of old-growth characteristics in managed stands where this is appropriate. This may require longer rotations, and the use of two or even three-storied high forest, group selection, or small patch cuts systems where these are ecologically and silviculturally feasible. The alternative is for a continuation of the transfer of significant areas of the timber production land base to unmanaged old-growth reserves. The area of old-growth stands reserved from logging will increase anyway as the province's ecological reserves system is completed and additional parks are created. But by appropriate changes to silviculture, timber production and old-growth values could probably coexist in some areas.

f. Because we have no experience of the rotation-length consequences of current harvesting impacts in most of the forests of British Columbia, nor of the alternatives we might wish to institute, it is difficult to compare their relative outcomes. Because current yield prediction models used in the province are insensitive to the question of soil damage and the sustainability of yield, they do not provide suitable predictive tools with which

to rank the various alternatives. Although reductions in AAC's are made to account for estimated losses in site productivity, there is a great paucity of empirical evidence as to how large these reductions should be. There is therefore an urgent need to develop, test, and implement ecosystem-level planning tools by which to rank the probable consequences of different harvesting strategies, in association with various different combinations of other silvicultural practices, for a variety of resource values. Only when we have scientifically-sound predictors of this type will we be in a position to select the harvesting and silvicultural strategies that will give the best overall management results over multi-rotation time scales. This would seem to be a more logical approach than simply reducing AAC's when evidence suggests that the harvesting and/or other management practices have reduced site productivity. Such models are not needed to prevent the more obvious examples of damage to soils and the aesthetic quality of the landscape. However, they are needed to rank the long-term consequences of various alternative solutions to these problems, and to predict some of the less visually obvious long-term impacts of timber harvesting.

g. Harvesting systems must be developed that are ecologically-sensitive and will result in sustainable development of a variety of forest-based resource values. They must be site and site condition-specific (as defined in Pre-harvest Silvicultural Prescriptions), and must be an integral part of a sustainable, rotation-length silvicultural system that will satisfy the management objectives for each particular site and for the overall forest management unit. The type, spatial pattern, and rate of harvesting must be designed to maintain a defined temporal pattern of local and regional biological diversity over the rotation, and the desired temporal and spatial patterns of abundance of designated wildlife species. Fish habitat and the quality, quantity, and regimen of streamflow must be maintained, allowing for the fact that various habitat and water characteristics will vary over the life of the tree crop. The harvesting systems must be sensitive to local concerns about aesthetics, must reflect the recreational and visual values of the area, and must consider the impacts on the native peoples and their way of life.

Designing harvest systems that satisfy all of these criteria requires a comprehensive inventory of all the significant resource values in an area, an explicit statement of the objectives of management with respect to these values, a formal plan as to how the objectives for each of these resource values are to be satisfied, and a monitoring and record-keeping system to ensure that goals are achieved. Many of the problems with timber harvesting conflicts in the province can be attributed to this lack of an adequate management planning framework in the past, or to a failure to implement or adhere to established plans and regulations. Institutional adjustments should be sought that would integrate more closely the management planning for the various

different forest-based resource values. Integrated land use management plans should be developed by multi-disciplinary management teams, the structure and terms of reference for which should be decided by the objectives of management.

h. Much of the public's concern about forestry arises because of a general antipathy towards clearcutting. There is a widespread lack of understanding about the ecological, silvicultural, and management reasons for this type of harvesting, and about when and where it is or is not ecologically appropriate. The forestry profession must invest many more resources in assisting the concerned sectors of the public to understand the positive and negative aspects of a variety of different harvesting systems, the reasons why they are used, and the social and environmental constraints that determine which harvesting systems could and should be used in a particular type of forest. This investment should not take the form of high-priced media advertising, but should focus on developing scientifically accurate educational aids for schools, demonstration forests, public involvement projects (eg. "adopt and manage a hectare of forest " projects), and public tours of forests. Only if the public is informed about the social and scientific basis for forest resource management decisions will the democratic process lead to forest policy and regulation that ensures the conservation of all the values of the forest for society, and the sustainable development of our forested landscapes.

Complementing these public education activities, the forestry profession must engage in a critical self-examination. Old methods and techniques must be replaced where they are no longer appropriate, and there must be a willingness to listen to the public and institute those changes that are ecologically-sound, silviculturally effective, and commensurate with the overall social goals of the province.

REFERENCES CITED

Dyck, W.J., C.A. Mees, & N.B. Comerford 1989. Medium-term effects of site-preparation on radiata pine productivity in New Zealand on a retrospective approach. In: W.J. Dyck & C.A. Mees (eds). Research Strategies for Long-term Site Productivity IEA/BE Project A3, Report No. 8. FR1 Bull. No. 152. Ministry of Forests, Forest Research Institute, Rotorna, N.Z.

Keeves, A. 1966. Some evidence of loss of productivity with successive rotations of Pinus radiata in the south-east of South Australia. Australian Forester 30:51-63.

Schwab, J.W. 1988. Mass wasting impacts to forest land: forest management implications, Queen Charlotte timber supply area. pp 104-115 In. J.D. Lousier and G.W. Still (eds). Degradation of Forested land: "Forest Soils at Risk". Proc. 10th B.C. Soil Science Workshop. Land Management Report No. 56. Ministry of Forests, Victoria, B.C.

Smith, R.B., P.R. Commandeur, and M.W. Ryan 1986. Soils, vegetation, and forest growth on landslides and surrounding logged and old-growth areas on the Queen Charlotte Islands. Land Management Report No. 61. Ministry of Forests, Victoria, B.C. 95pp.

Squire, R.)., P.W. Farrell, A.W. Flim, and B.C. Aeberli 1985. Productivity of first and second rotation stands of radiate pine on sandy soils. I. Site factors affecting early growth. Australian Forestry 42(6): 226-235.

Utzig, G.F. & M.E. Walmsley 1988. Evaluation of soil degradation as a factor affecting forest productivity in British Columbia: a problem analysis. Phase 1. Contract Report 025. FRDA. Canada/B.C. 111pp & app.

APPENDICES

I. Biogeoclimatic map of British Columbia

II. Three papers on the use of ecosystem management simulation models in yield prediction:
    Forestry Chronicle 1985
    Eddy Lecture 1986
    Modelling Symposium Lecture 1990

III. Paper on old-growth forests from the 1990 McGraw-Hill Yearbook of Science and Technology.

BIOGEOCLIMATIC MAP OF BRITISH COLUMBIA

THREE PAPERS ON THE USE OF ECOSYSTEM MANAGEMENT SIMULATION MODELS IN YIELD PREDICTION:

FORESTRY CHRONICLE 1985
EDDY LECTURE 1986
MODELLING SYMPOSIUM LECTURE 1990

Future Shock in Forest Yield Forecasting: The Need for a New Approach

by

J.P. Kimmins[1]

Abstract

The traditional method of predicting future yields of conventional forest products and/or biomass is based on an empirical bioassay of the growth potential of unmanaged stands, or of stands subject to one, or a small number of, management practices. The method employs the historical pattern of stem volume and/or forest biomass accumulation in the form of volume- or biomass-over-age curves. This type of yield predictor, which may be presented as a simple yield table or a more complex mensurational computer yield model, is widely considered to produce believable future yield predictions. However, the predictions will only be accurate if the future environmental conditions and management regimes are similar to those that pertained over the period during which the biomass accumulation on which the yield model is based occurred. This is unlikely because the continued growth of the human population and the resultant loss of forest land will require a great intensification of forest management. The significant changes in management that many believe await forestry in the not-too-distant future in many parts of the world will render such conventional predictions very questionable. In addition, human-induced changes in atmospheric chemistry may result in changes in the climatic (the "green-house gases" problem), canopy or soil conditions (the "acid rain" problem) that determine tree growth.

Computer models of forest yield based solely on the simulation of the biological processes that determine tree growth do not at present offer a viable alternative. Either we do not yet know enough to build, or we do not have sufficient resources to develop and calibrate such process models at an adequate level of complexity.

What is needed is a generation of hybrid yield models that combine traditional mensurational models with a simulation of those growth-regulating pro-

[1]Professor of Forest Ecology, Faculty of Forestry, University of British Columbia, Vancouver, B.C. V6T 1W5

Résumé

La méthode habituelle de prédiction des rendements futurs des produits forestiers conventionnels ou encore de la biomasse est basée sur une bio-estimation empirique, du potentiel de croissance de peuplements non-aménagés, ou de peuplements soumis à une ou à un petit nombre d'interventions sylvicoles. Cette méthode utilise le schème habituel du volume de la tige représenté par une courbe en fonction de l'âge et de l'accumulation de la biomasse forestière en fonction de l'âge. Ce genre de prédicteur du rendement, qui peut prendre la forme d'une simple table de rendement ou d'un complexe modèle informatisé de rendement tiré de données dendrométriques, est largement considéré comme pouvant produire des prédictions valables des rendements futurs. Toutefois ces prédictions ne seront précises que si les conditions environnementales et les régimes d'aménagements futurs ne sont semblables à ceux qui prévalaient au cours de la période pendant laquelle l'accumulation de la biomasse s'est faite pour établir le modèle de rendement. Cela est loin d'en être le cas puisque la croissance continue de la population humaine et les pertes occasionnées par le fait même au domaine forestier nécessiteront de plus amples travaux d'aménagement forestier. Les changements significatifs en aménagement qui semblent attendre la foresterie dans un futur pas très éloigné dans plusieurs régions du monde mettront en doute de telles prédictions conventionnelles. De plus, les changements causés par l'homme dans l'alchimie atmosphérique peuvent aboutir à des modifications des conditions climatiques (le problème de l'"effet de serre" des gaz), dendrologiques ou pédologiques (le problème des "pluies acides") qui affectent la croissance des arbres.

Les modèles informatisés de rendement forestier issus seulement d'une simulation des processus biologiques qui affectent la croissance des arbres ne représentent pas à ce moment une solution viable. Nous n'en savons pas encore assez pour construire, ou nous n'avons pas les ressources suffisantes pour développer ou pour calibrer de tels modèles de processus à un niveau adéquat de complexité.

Nous avons besoin d'une génération de modèles hybrides de rendement qui inclut les modèles dendrométriques traditionnels et une simulation des processus régulateurs qui sont significativement modifiés par un chagement des pratiques sylvicoles ou encore aussi par un changement de l'alchimie atmosphérique et du climat. L'un de ces modèles est FORCYTE: "The

cesses that are significantly altered by changing management practices and/or by changing atmospheric chemistry and climate. One such model is FORCYTE: the FORest nutrient Cycling and Yield Trend Evaluator. This is an ecologically-based forest management simulation model that can predict the long-term consequences of a wide variety of forest management practices for the future harvest yield, ecosystem nutrient budgets, economic efficiency and the energy benefit/cost ratio of management. It combines the believability of the traditional approach with the flexibility of ecological and biological process simulation. Present versions of the model focus on the consequences for future production and yield of changes in forest management. However, because of the structure of the model, it is capable of being modified to examine similar consequences of climatic change and alteration in atmospheric chemistry. Progress in the latter area must await clarification of the processes involved in acid rain damage to forests. FORCYTE is also capable, with minor modification, of being used in agriculture and mined land reclamation research and planning.

Key words: Yield prediction, FORCYTE

FORest nutrient Cycling and Yield Trend Evaluator" Il s'agit d'un modèle de simulation de gestion forestière basé sur l'écologie, qui peut prédire les conséquences à long terme d'une grande variété de pratiques sylvicoles sur le rendement futur de la récolte, les échanges d'éléments nutritifs dans l'écosystème, l'efficience économique et le ratio coût-bénéfice énergétique de la gestion. Celui-ci combine l'approche reconnue de la méthode traditionnelle ainsi que la flexibilité du processus de simulation ainsi que la flexibilité du processus de simulation écologique et biologique. Les versions actuelles du modèle mettent l'accent sur les conséquences qui surgiront des changements de la gestion sylvicole sur la production future et le rendement. Toutefois, à cause de la structure du modèle il est possible de le modifier pour en examiner aussi les conséquences issues des changements climatiques et des modifications de l'alchimie atmosphérique. Des progrès dans ce dernier domaine doivent attendre une meilleure compréhension des processus mis en cause lors des dommages causés par les pluies acides aux forêts. FORCYTE est aussi en mesure, suite à quelques petites modifications, d'être utilisé en agriculture et en planification et recherche sur la rétrocession des terrains miniers.

Mots clés: Prédiction du rendement, FORCYTE

Introduction

Forestry is unique amongst human economic endeavours in that, in addition to short-term planning, it also has an extremely long planning horizon. There are very few major economic activities that involve such a long time before a return on investment is realized, and which require such an act of faith in the future.

The future has a great effect on what foresters do in the present because the calculation of the annual allowable cut involves a prediction of future increment (cf. the annual allowable cut effect). Consequently, foresters who claim to be practicing sustained yield management must consider the medium- and long-term, as well as the short-term future. Our management must certainly be economically, managerially and environmentally sound this year and over the next five to ten years, but we can only judge the wisdom of our current actions if they are also considered in terms of the expected condition of the forest resource at the end of the next rotation. As good stewards of the land, foresters aspire to the achievement of sustained or increased yield over several rotations. This means that, like it or not, we foresters are in the game of making long-range management projections in general, and long-range yield predictions in particular.

We all hate to change the way we do things, especially when our current methods seem to have worked fairly well in the past and some of the alternatives didn't. This certainly appears to be true of yield prediction in forestry. Many foresters are deeply committed to the traditional empirical mensurational approach and have tended to look askance at the efforts of forest scientists to develop biological process computer simulation models of forest growth as a basis for yield prediction. However, although traditional yield prediction methods have until recently been considered by many to be both satisfactory and superior to the alternatives, new approaches are now needed. My argument is based on two major points:

(1) human population growth, and the important consequences that this has for forests, and
(2) the need for a prediction system that recognizes the complexity of the forest ecosystem, the significance of this complexity for the success with which we can predict yield, and the effect of various combinations of forest management practices on the functioning of this complex natural system.

In this paper I shall elaborate these two topics to demonstrate the need for a new approach to yield forecasting. An example of one new approach, the FORCYTE model, will then be discussed briefly.

Human Population Growth and Its Consequences for Forestry

There is no single more important determinant of the medium- to-long-term future of forestry than the growth of the human population. It affects every aspect of forestry, from the demand for lumber and other forest products, to the land base available for growing trees, and the biological, chemical and physical conditions under which tree crops grow.

Forest clearance to make way for agriculture to feed the growing human population is predicted to convert large areas of tropical and sub-tropical forest land to agriculture and/or scrub forest over the next 80 years, and even in temperate latitudes significant areas of the most productive forest land may be assigned in the future to food production. It also seems to be inevitable that yet more productive valley forests will be flooded for hydro-electric schemes, and for water storage for

agricultural, urban and industrial use. More forest land will undoubtedly be sequestered for recreation and other non-consumptive uses. Unless acid rain is controlled, increasing areas of forest at industrialized temperate latitudes may experience significant or even total reduction of forest growth. If the growing population continues to release more CO_2 and other "greenhouse gases" into the atmosphere, the risk of global warming and significant climatic change will increase from the realm of possibility to the realm of probability, with potentially adverse effects on many areas of forest.

I know of no well-qualified demographic expert who predicts much less than a doubling of the present (4.6 billion) human population to about 9 billion. Many predict close to triple (11 to 12 billion: e.g. World Bank, 1984) and some have even suggested that quadruple (16-20 billion) the present levels may be achieved before the population ceases to grow (Figure 1). Based on this range of demographic predictions, I advance the following premises and corollaries therefrom.

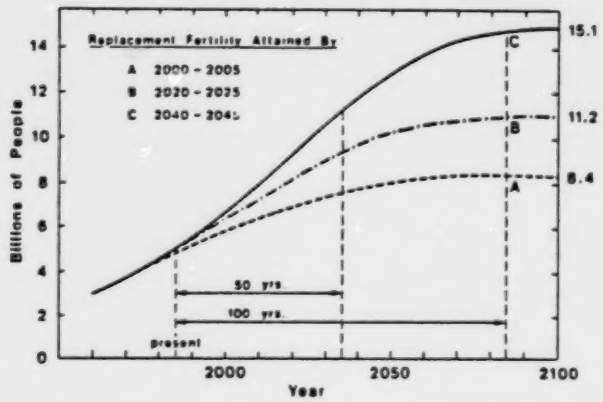


Figure 1. Probable growth of the human population according to three assumptions on when global replacement fertility is achieved: A. 2000-2005, B. 2020-2025, and C. 2040-2045 (i.e. 15-20 years, 35-40 years and 55-60 years from now) (van der Tak *et al.*, 1979). Replacement fertility is the birth rate per 1000 people that equal as mortality rate per 1000 people. Population growth will continue after replacement fertility is achieved because of the unstable age distribution of the human population: much of the world's population are young and have not yet reproduced. The number of females in the reproductive age classes will continue to increase for many decades to come and even if their rate of reproduction per 1000 is quite low, the total number of babies born per year will continue to exceed the total number of people dying per year for quite a long time. A population that has an unstable age distribution thus has a momentum to its growth so that population growth continues for some time after birth rate (per 1000) has been reduced. The World Bank (1984) predicts a stable population level in excess of 12 billion. The expected population 50 years from now and 100 years from now is shown for each assumption.

Premise 1: World population is continuing to grow and will most probably exceed 8 billion by the end of the next rotation of most temperate and northern coniferous crops (assuming rotations of at least 50 years).

Some statistics to support this premise are that by 2020 (35 years from now), Canada's population is predicted to have risen by 11 million (a 44% increase), the U.S. population by 62 million (a 26% increase), and the world's population by 3233 million (an increase of 67%) (Kane, 1983).

Corollary: A significant proportion of the world's present forest area will be cleared of trees to provide food growing areas and/or water reservoirs to supply this growing population.

Estimates of the rate of net world deforestation range from about 12 ha/min. to about 45 ha/min., or about 6 to 24 million ha/yr (most of this is in the tropics and sub-tropics). The area of closed forest around the world is expected to decline 17% by 2000, growing stock will decline by 23%, while the human population will grow by 49% (Council on Environmental Quality, 1981; Brown *et al.*, 1984).

Considering that the growing world demand for industrial wood is expected to exceed the projected world supply early in the next century (Industrial Working Party, 1982), some degree of timber famine will become the inevitable lot of the majority of the world's population for the foreseeable future. This condition, which has been chronic in "third world" countries for decades already, will continue to worsen (Brown *et al.*, 1984).

Premise 2: Greatly increased forest production will be demanded from the remaining forest land to satisfy the demands of the growing population.

Corollary: To achieve greater production from less land, forest management will become much more intensive, including shorter rotations, better site preparation, prompt regeneration with genetically improved trees, effective brush control (vegetation management), stand density control, fertilization, more complete utilization.

As a result, the site conditions under which forest trees grow will in many cases be significantly different from those of the past.

Premise 3: Human population growth will sustain the recent trends in alteration of atmospheric chemistry associated with "greenhouse gases" (Clark 1982) and emissions of gaseous oxides of nitrogen and sulphur (Morrison 1984, Smith 1985) for long enough to result in biologically-significant alterations in regional climates and ecosystem processes, respectively, in at least some parts of the world.

Corollary: Where there are significant changes in temperature and precipitation patterns, future forest growth can be expected to deviate significantly from the historical patterns for the area.

Corollary: Where atmospheric acidification results in sustained and widespread "acid rain" phenomena, significant changes in forest growth may be expected at some time in the future in some or all sites in the affected area.

The very considerable uncertainties associated with both the "greenhouse effect" and "acid rain" phenomena make it

difficult to predict with any certainly what those environmental concerns will mean for future forest growth However, the evidence is increasingly persuasive that, if this premise is correct, these two human-induced alterations of the global environment will result in appreciable changes in growth environment for trees in many parts of the world

The important conclusion from this section is that human population growth will result in significant changes in the environmental conditions that determine forest growth, so that the past record of growth on a particular site will become a questionable basis on which to predict future growth on that site As we shall see, this raises serious questions about the believability of traditional yield forecasting methods

However before analysing the strengths and weaknesses of available yield prediction systems, we must consider the basic nature of prediction in complex systems

Prediction in Complex Systems: The Need For a New Method of Predicting The Productivity and Yield of Forest Ecosystems

One of the most important Canadian papers in ecology was written by Rowe (1961) In it he noted that biological systems can be ranked into "true levels-of-biological-integration" Such levels can be defined as the total environment of the levels of biological organization below them Three true levels of integration are identified: cells, individuals and ecosystems Neither populations nor communities are true levels-of-integration, even though they are legitimate levels of biological organization and objects of study Populations are not the total environment of individuals, nor are communities the total environment of populations or of individuals Individuals, populations and communities exist in landscapes (i e ecosystems), not as isolated entities The ecosystem is thus the environment for all of these levels of biological organization.

Rowe pointed out that events or conditions at any level of biological organization (e g individuals, populations or communities) can only be completely explained, and thus predicted, on the basis of knowledge of the next true level-of-integration above (i.e ecosystems) Conversely, understanding individual biological processes at any level of biological organization generally involves a knowledge of lower levels of biological organization For example, a complete understanding of plant growth requires a knowledge of cellular physiology However, neither a knowledge of cellular physiology, nor an understanding of the population processes of competition and mortality, will provide, on its own, an accurate prediction of the future growth of a forest in its natural landscape (ecosystem) setting

Accurate prediction of the future of populations (e g a herd of deer, a stand of trees) can only come from a knowledge of the complex assemblage of biotic *and* abiotic factors that affect that population This suggests that yield prediction in tree populations or forest communities should be approached from the ecosystem level-of-integration rather than from the individual tree, tree population (i e stand) or community level This concept is illustrated in Figure 2. Based on these ideas and on the above three premises and their corollaries, I advance the following additional premises and corollaries.

Premise 4: Because increased production will be required from a dwindling forest land base, silviculture and forest management must become more successful and there must be fewer "mistakes" Inappropriate management practices that take forest land permanently out of production, that cause a delay in production or which lower the productivity of the land on anything more than a temporary basis will be increasingly unacceptable.

Corollary: Yield forecasting must be conducted using a method that will give accurate predictions and will permit a comparison of the expected yield consequences of a variety of alternative management strategies This requires that yield prediction models be developed at the ecosystem rather than at the population or community level of biological organization Because of the spatial complexity of forested landscapes, such yield predictors should be ecosystem-specific and should be used in conjunction with some system of ecological site classification (e g biogeoclimatic classification Krajina 1969, 1972; Kojima, 1981, Klinka *et al.*, 1980).

Corollary: Because a wide variety of site preparation and stand management activities have implications for future productivity and yield, environmental impact assessment (EIA) tools must be developed that will permit foresters to assess the long-term yield consequences of their management activities Yield forecasters should incorporate the ability to undetake EIA of alternative stand management strategies

Premise 5: Because the conditions under which trees will be grown in the future will frequently be significantly different from those of the past, traditional methods of yield prediction which are based on an empirical bioassay of past environments will, on their own, have greatly reduced value for predicting future yields They will not provide the degree of accuracy or flexibility that will be required in the future

Corollary: There is an urgent need to develop and apply new methods by which to make accurate predictions of the short-, medium- and long-term yield, environmental and economic consequences of current, as well as of new and frequently untried, forest management strategies — strategies that will have to be used if we are to get increased yield from a diminishing land area at a reasonable economic cost

If we are to avoid using management practices that lower yields and the productivity of the land, thereby increasing the cost of sustaining forest production, we must have better methods of predicting the outcomes of our management.

The current momentum of human population growth is going to revolutionize forestry over the next forty years, just as growth over the past forty years has revolutionized agriculture The future of forestry is certainly not going to be the same as the past Traditional methods of yield prediction based on historical growth patterns achieved under the relatively stable and unchanging environmental conditions and management regimes of the past are probably the best practical yield predictor for a future that is the same as, or very similar to, the past However, their predictions are not very believable in a significantly different future

Because of accelerated rates of change in management methods, the time available to gain empirical evidence of the consequences of alternative future management strategies will decrease, making it difficult to go on relying solely on tradiional, empirical methods of developing yield predictors New approaches to yield prediction are required that can accommodate changes in future management without waiting the many years that are required by the traditional method To

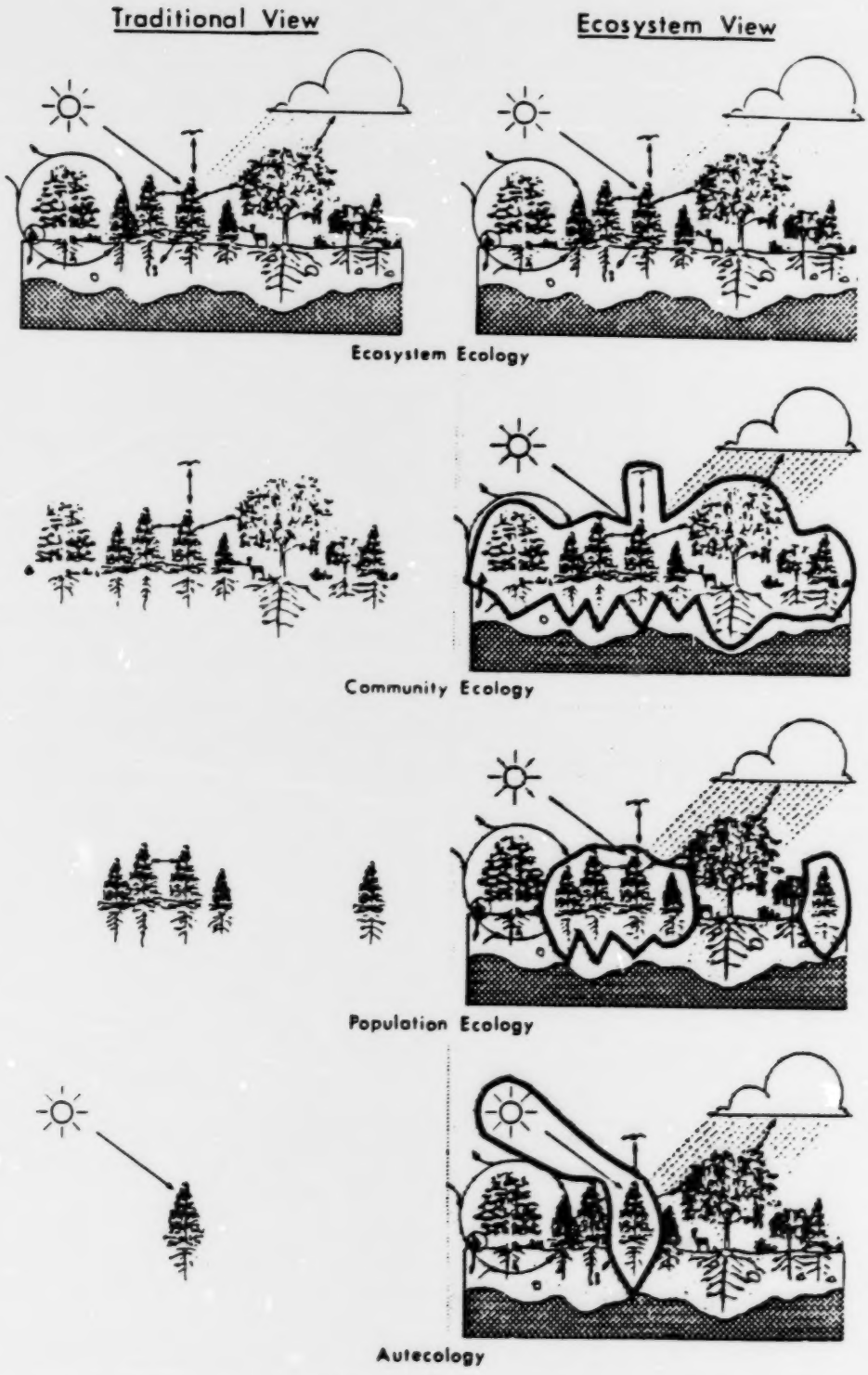


Figure 2. "Traditional" and "Ecosystem" views of the subdivisions of ecology. In the traditional view, ecosystems are disaggregated into biotic communities (biotic community is the focus of attention); biotic communities are disaggregated into populations (individual species populations are the focus of attention); populations are disaggregated into individuals (the individual and its physiology is the focus of attention). In the ecosystem view, the attention may focus on any one of these levels of biological organization, but *always* in the context of the ecosystem framework in which the level exists. The ecosystem view ensures that all major determinants of events or conditions are considered no matter what the focus of attention. Prediction of future events at the individual, population and community level is likely to be much more successful using the "ecosystem view" than the "traditional view".

achieve the desired accuracy in predicting yield in changed forest environments we need a more flexible type of model that can take account of how intensification of local stand management and/or changes in global conditions will influence growth processes. Because we are managing landscapes not tree populations we must use ecosystem-level rather than population-level models.

Before proceeding to a discussion of a possible design for a new yield prediction system, we shall examine more closely the strengths and weaknesses of the two major approaches that are currently available: traditional empirical systems and biological process simulation systems.

The Strengths and Weaknesses of Traditional and Process Simulation Approaches to Yield Prediction

(a) Traditional empirical models

Traditional methods of yield prediction are based on an empirical, historical bioassay of the total, integrated forest ecosystem. They predict future growth by projecting from the historical record of past growth. As such, they are ecosystem level models. They satisfy Rowe's requirement that in order to make a prediction of events (yield) at the population level (stand of trees), one must either consider explicitly, or account implicitly, for processes and events at the next true level-of-integration above (the ecosystem). This is done implicitly in empirical models by means of the bioassay of past tree growth which has integrated all of the factors determining tree growth on the site over an extended period of historical time.

. Other advantages of traditional methods of yield prediction include the fact that they do not rely on our still incomplete understanding of many aspects of how ecosystems work, nor are they restricted by the time, manpower and financial constraints that often limit our ability to gather detailed information on those major determinants of tree growth that we do understand reasonably well.

On first consideration, it might thus seem that the traditional empirical yield predictors are all that we need. However, there is the one major shortcoming that has already been mentioned. Just as regression equations are only valid over the range of data from which they were derived, and just as single-factor regression models are only valid if other factors (independent variables) that influence the dependent variable-independent variable relationship (but are not represented) remain the same, empirical models are only valid for the environmental and management conditions under which the tree growth on which they are based occurred.

If the future is the same as the past, we do not need new types of yield predictors. But *if* the future is different, and there is compelling evidence that it will be (see above discussion), then, as with a regression equation applied outside of the range of its data, or a single-factor equation applied under very different circumstances, the predictions of traditional, empirical yield models, on their own, are very questionable. Because such models only account for ecoysystem processes implicitly, they are inflexible, and in the absence of empirical response data they cannot deal readily with management-induced change in those processes or changes associated with atmospheric alteration. This is true of both conventional yield table models and mensurational computer simulation models. Multiple regression models are able to deal with several independent variables at the same time and constitute a great improvement over single-factor equations but they also tend to have problems of inflexibility because as with most process models (discussed below) they usually do not include sufficient complexity to make them truly ecosystem-level models.

(b) Process simulation models (sometimes referred to as "biological" models)

During the late 1960's and the 1970's there was a flurry of activity by biologists and ecologists in process simulation modelling of forest growth. The dependent variable of growth was related to a number of independent, growth-determining variables, and these relationships were combined in computer models to become the basis of a simulation of growth. Modellers in the International Biological Program and others since then who have adopted this approach have made great contributions to forest science by providing an excellent mechanism for the synthesis of knowledge, ideas and data by guiding research through the identification of knowledge gaps and by the creation of interesting, testable hypotheses.

There is no fundamental reason why it should not eventually be possible to produce believable predictions of the future functioning of an entire ecosystem based solely on a knowledge of ecosystem processes. However, as a class of model, biological process simulators have not yet proven to be very useful (i.e. believable) as practical, long-term predictors of forest productivity and yield. This failure results from one or more of the following:

(1) the lack of detailed, site-specific knowledge of many ecosystem processes.
(2) the failure to include existing knowledge of ecosystem processes in such models (e.g. attempting to predict the population event of growth using knowledge from the population level, rather than from the ecosystem level of integration, or the omission from a model of one or more major determinants of growth).
(3) technical and/or economic difficulties in obtaining the data necessary to adequately calibrate process models that do describe these ecosystem processes.

Points 1 and 2 refer to the fact that process models have generally not had sufficient complexity to make them truly ecosystem-level models, while point 3 refers to the practical difficulties that attend the development and use of ecosystem-level process models.

The major practical value of process models has been in revealing areas of inadequate understanding of ecosystems and in guiding research, rather than in marshalling what we do know into a usable predictive framework for forest land management. Process models are attractive in that they offer an explanation for some aspects of how ecosystems work, and they have the flexibility to deal with future change in those processes — a flexibility that traditional empirical models lack. However, there is little reason to believe, given our present knowledge, that biological process simulation models should be able, on their own, to accurately predict future states of an entire, complex ecosystem, and in particular, the tree growth component thereof. Scientists still require the empirical crutch of a bioassay in making believable predictions of the behavior of biological systems as complex as forests far into the future. This has lead some foresters to believe that it is a waste of time to try to predict the future with such models, and these foresters have rejected the concept of process modelling in yield prediction.

Both the traditional empirical and the biological process simulation approaches to yield forecasting have advantages and strengths, but they also both suffer from weaknesses that render them unsuitable, on their own, as the yield prediction system of the future. In the next section I shall suggest an alternative approach that offers a considerable improvement on these two systems.

What Type of Model Will Give The Best Long-term Predictions of Forest Yields?

I believe that the best approach to making long-term yield predictions in forestry, given our present scientific understanding, is to develop models that are a hybrid between the traditional and the process simulation approaches: models that are ecologically sound in that they integrate implicitly, through a historical bioassay, all the significant determinants of growth on a site (and are therefore ecosystem level models), but which also simulate those aspects of ecosystem structure and function that are significantly changed by changing management and/or changing climatic conditions. Such models would have a believable ecologically-sound predictive foundation but would also have the flexibility to account for the effects of changes in management and/or for the effects of human-induced global alterations in atmospheric conditions on these historically-based predictions.

No, we do not need to simulate every minute ecosystem compartment and process to produce a useful management/yield predictor, because by using an historical bioassay we obtain an implicit integration of the yield consequences of much of the complex structure and function of the ecosystem. Anyway, we do not yet have either the knowledge or the data to undertake a detailed simulation of all aspects of an ecosystem, and generally we do not have the money and time to collect all the data that would be necessary even if we did have the knowledge. But we do have much of the knowledge and data needed to build usable hybrid empirical-process models. It is time to harness the knowledge and data that are a product of 35 years of basic forest research and put them to use in improving our ability to predict the consequences for future yields and economic performance of our management activities, thereby helping foresters to make wise choices between management alternatives.

What types of process should be simulated in such a hybrid model? To answer this we need to consider the forest in its most fundamental terms: energy (Figure 3). A forest is a natural energy-processing/storage system in which energy accumulates in various compartments (plants, herbivores, decomposer organisms, etc.) as a result of the balance of energy gains and losses to and from those compartments. The energy flows are regulated by a variety of factors that can be classified into three major groups:

1. Factors largely uninfluenced by forest management

Site factors such as regional temperatures, wind patterns, frost-free growing season and day length play a major role in determining tree growth and other energy flows, but they are mostly unaltered by local forest management. Their effect is implicit in empirical tree growth data and need not be simulated explicitly. Extremely large-scale deforestation may have the potential to alter regional climates, but changes in the intensity of local stand management are unlikely to have such an effect. However, changes in micro-climate and such phenomena as cold-air drainage may, in some cases, require representation, and if one wishes to predict the consequences for future yield of human-induced alterations in climate and weather, the effects of these regional site factors must be included in some way.

2. Factors partially under the influence of forest management

Site factors such as soil moisture and soil aeration are very important in determining tree biomass accumulation rates, but in most cases they are more or less permanent site features whose effect on tree growth is reflected implicitly in traditional yield tables. However, on some sites these factors may be significantly altered by changes in management (soil compaction, soil drainage, loss of soil organic matter and soil structure), so it may be desirable for a yield model to have the ability, as a simulation option, to examine the consequences for tree growth and yield of changes in these site parameters.

Diseases, insects and fire are also factors that influence tree growth, but unlike the continuous site factors of climate and soil, they are generally episodic. Because they are to some extent under the control of the manager (who can alter the fire, insect, and disease conditions that pertained during the period of forest growth on which the empirical bioassay is based), it is desirable for a model to be able to simulate explicitly the effects of these three factors on yield. However, these processes rank lower in priority for simulation than those in the third category.

3. Factors that are largely controlled by the forester

The silvicultural factors of species, genotype, stand density and brush competition have a major influence over tree biomass accumulation, and all of them can be strongly influenced by the forester and by changes in forest management. They should, therefore, be represented in a yield prediction model. Differences in species genotype can simply be represented by using different empirical growth curves, but prediction of the effects of stand density manipulation and brush control on biomass accumulation and yield requires a simulation of light profiles, of competition for light and of the effects of shading.

In addition to silvicultural considerations, there is the site factor of nutrient availability. This is the site factor that is most easily influenced by management and is very susceptible to change as management is intensified. It is also subject to alteration by such phenomena as acid rain. The relationship between tree growth and nutrient availability should therefore be simulated in a yield prediction model.

A minimum design requirement for a hybrid empirical-process stand yield model is that it should include the factors in group three: a simulation of light profiles and the effects of shade on growth, and of nutrient availability and its effects on growth. It is also desirable that such a model have the ability to simulate those factors in group two that are germane to the particular situation that is to be simulated: e.g. one or more of the effects of fire, insects and disease and of changes in site moisture status and soil compaction on yield. One example of such a model is FORCYTE (FORest nutrient Cycling and Yield Trend Evaluator (Kimmins and Scoullar, 1983, 1984, 1985) (Figure 4). Inclusion of some of the factors in group one will be necessary if one wishes to examine the effect of climatic change on forest growth. The current version of FORCYTE does not have this capability and is therefore limited to the analysis of stand management effects on yield. However, the

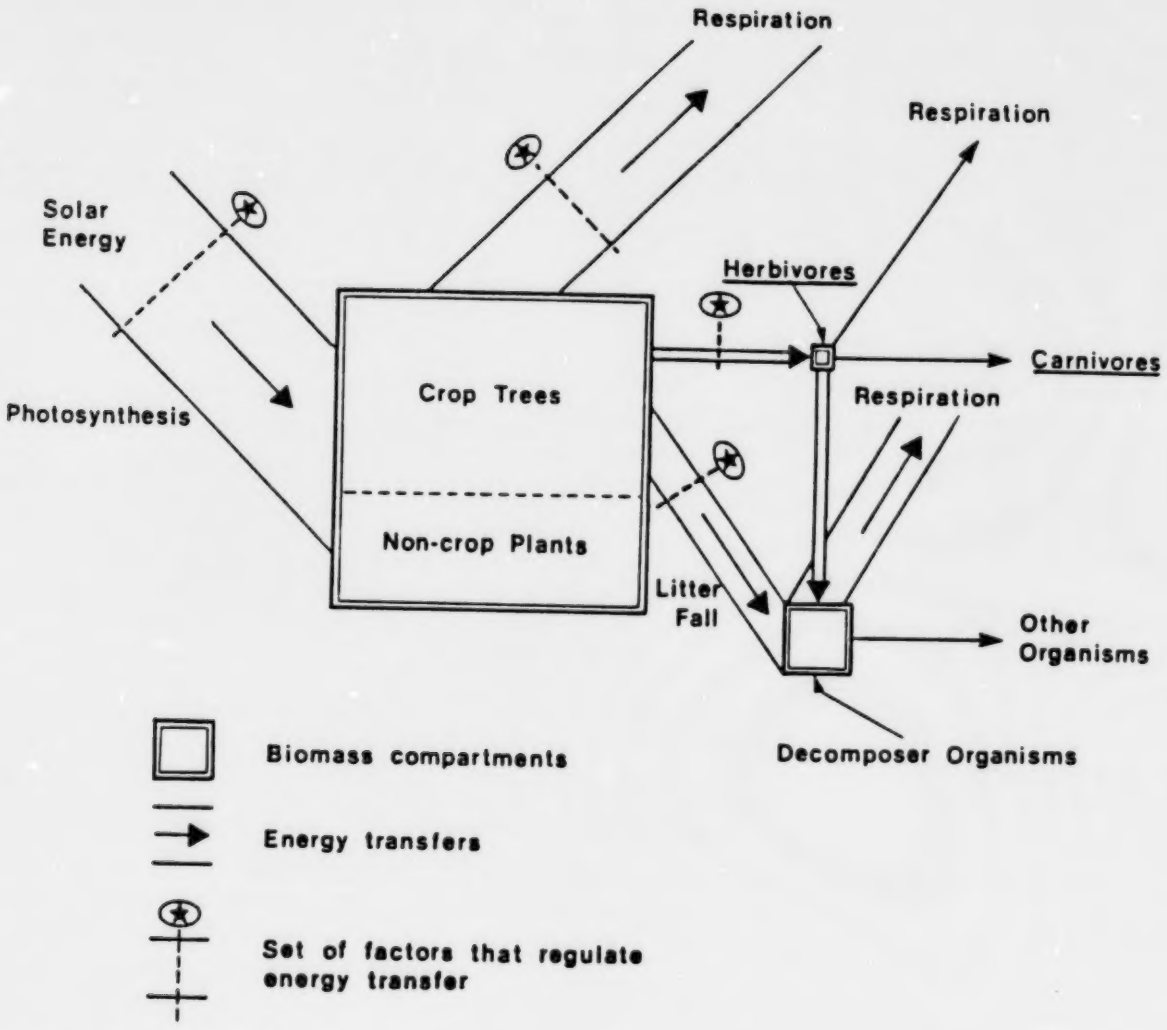


Figure 3. The forest ecosystem represented as an energy-flow diagram. Biomass (i.e. energy) compartments (e.g. trees, herbivores, decomposer organisms) are represented as boxes; energy transfers into and out of the biomass compartments are represented as pipes. The rate of accumulation of energy (i.e. biomass) in any compartment is determined by the balance between inflows and outflows of energy. These flows are determined by a diverse set of abiotic (e.g. temperature, water, nutrients) and biotic (e.g. competition, predation) factors which act as flow regulating valves.

structure of the model would permit this capability to be added relatively easily.

Ecosystem-level Models and "Technology Transfer"

An important reason for the development of a hybrid, ecosystem-level forest management simulator is to provide a mechanism by which to facilitate the application of the products of basic forest research in operational forest management. Much good forest and environmental research conducted over the past few decades has never progressed beyond the scientific journals into practical applications in forest management. Scientific research tends to concentrate on subcomponents and/or individual processes of ecosystems, and although the results of such reductionist science is of unquestionable value to science, much of it is unusable by forest managers who must deal with entire ecosystem units. While such reductionist knowledge is a *necessary* prerequisite for the advancement of our understanding of forest ecosystems and their response to management, it is not *sufficient*. The integration and synthesis of such knowledge is also required. An ecosystem-based yield model can focus a wide variety of research data concerning ecosystem subcomponents and processes into predictions concerning future states of the forest ecosystem. Such a model can provide a practical justification for a wide variety of forest science activities, can act as a guide for future research, and can be a generator of hypotheses to be tested in critical experiments.

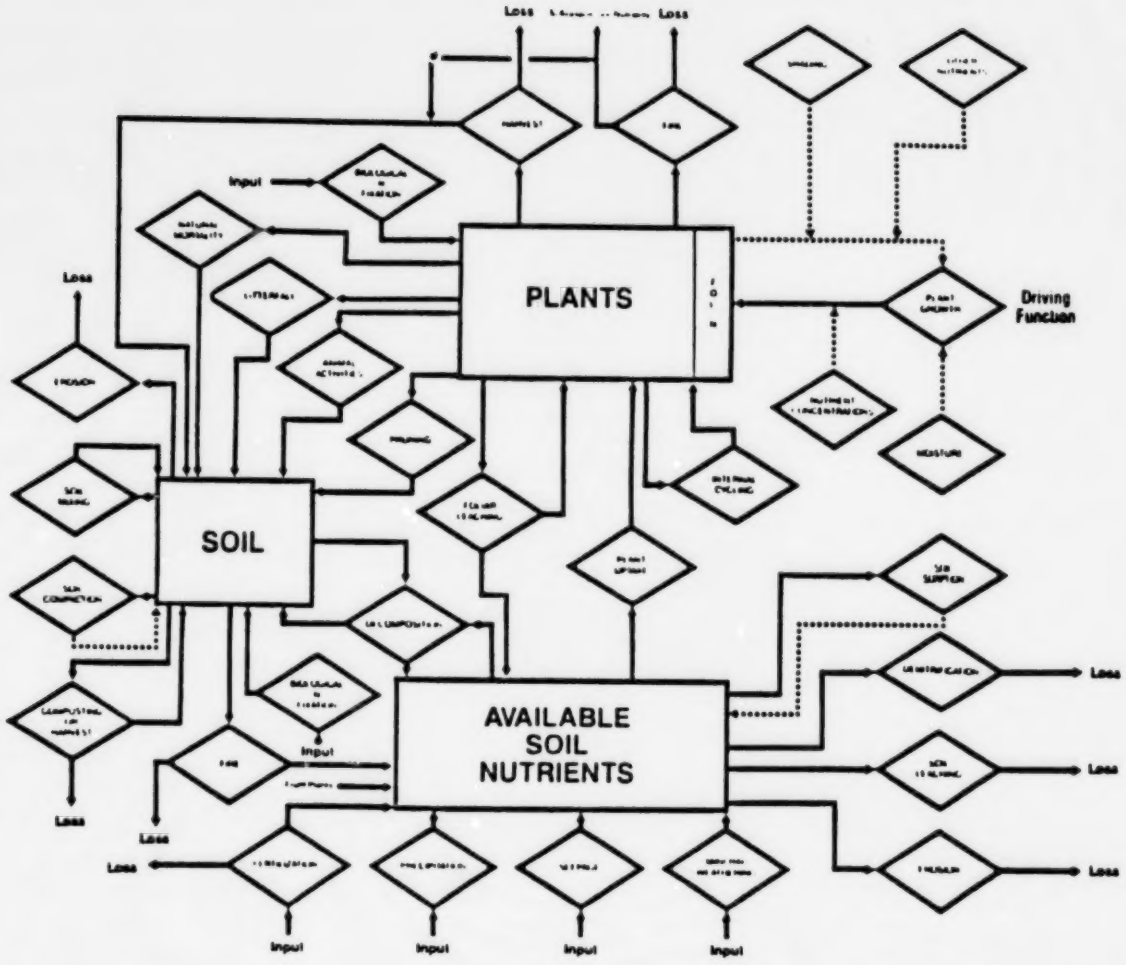


Figure 4. Flow chart of the 11th version of FORCYTE (FORest nutrient Cycling and Yield Trend Evaluator). The model consists of three major compartments: plants (trees, shrubs, herbs and/or mosses and their various different biomass components), forest floor (involving a detailed simulation of the decomposition of annual cohorts of all the major types of litterfall materials) and available soil nutrients. Most of the major natural and management-induced processes and pathways of biomass and nutrient transfer between compartments are represented.

Future Shock in Forest Yield Forecasting

Future shock[2] is finally coming to forestry. Certainly, things have always been changing, and the rate of change (expressed as a percentage annual change) has not undergone any dramatic alteration recently. However, it is a feature of the type of growth exhibited by the human population and its exploitation of resources (exponential growth) that a long period of relatively slow absolute change is followed by very rapid and dramatic increases in absolute values. This happens even if the proportional *rate* of change remains constant. Human population growth and resource exploitation have now reached the stage at which the *absolute* rate of changed has become so great that many of our institutions and mechanisms are no longer able to adapt and change fast enough. This "future shock" has been felt in many aspects of society for nearly half a century. It is beginning to be felt in forestry.

Mechanisms for predicting future yields that have successfully served generations of foresters are becoming inadequate because the absolute rate of change of the future has changed. This in no way implies the demise of the present generation of empirically-based stand models. Conventional yield models and their computerized equivalent will probably always have an important role to play in short-term and even medium-term yield prediction. But for the long-term predictions that are an inevitable component in the setting of realistic current allowable harvest rates in a rapidly changing world, and are necessary if we are to choose wisely between alternative management practices, hybrid yield predictors of the type I have suggested will be required. A large number of empirical yield models exists (see Trimble and Shriner, 1980), and many of them would make an excellent basis from which to develop ecosystem-level yield models. Alternatively, the output of the former can be used as the input to, and/or as a test of some of the predictions of, existing hybrid ecosystem-level models. There is also a large body of expertise in empirical and stand (population) modelling that provides an excellent technical resource for the development of new predictors. The ideas

[2]Toffler, A. 1970. Future Shock. Bantam, Toronto. 561 p.

presented in this paper should be viewed as complementary to and not in competition with this existing body of modelling activity

Future yield predictors should not only deal with yield Forestry is basically an economic capital-creating activity Many whole-forest models deal with economics but not all stand models do even though foresters are often more concerned with maximising *value* rather than *volume* or *biomass* Consequently the new generation of hybrid yield models should provide the user with an economic assessment And in a world in which fossil fuel energy is expected by some to get increasingly expensive within the time scale of forest crop production yield models of the future should also provide an evaluation of the energy efficiency of management Much of the cost of forest management is the cost of energy The difficulty of predicting future energy costs accurately is a major difficulty in making accurate long-term economic predictions in forestry Examination of the energy costs and benefits of forestry can be a useful adjunct to conventional economic analyses

More work remains to be done before the next generation of yield models are ready for widespread use However, models such as FORCYTE (Kimmins and Scoullar, 1983 1984 1985) and FORTNITE (Aber and Melillo, 1981) constitute a first step in that direction FORCYTE is currently being evaluated tested and/or used in Scandinavia, Great Britain, North America South America New Zealand Indonesia and Japan by university teachers and researchers government agencies and/or forest companies The results of this activity over the next few years should provide a good test of the utility of the approach suggested in this paper

Reminder

In closing the reader is reminded that models are mere representations of reality not reality itself To a greater or lesser extent, therefore, all models of biological systems are "wrong" Only reality is "correct" The most fundamental difference between different models is how "wrong" they are (i e how closely they approximate the reality they represent)

One can build a model of an aeroplane that does not look like a real plane but which mimics the flight of an aeroplane very closely Alternatively, there are exact miniature replicas of planes that do not fly If one makes a model that looks exactly like an aeroplane, flies like one, and performs all its normal functions it is no longer a model it is a real aeroplane Unfortunately, no such continuum exists for biological systems and models thereof One can build a model bird that sings and externally looks like a bird but does not fly One could even build a model bird that sings, flies and looks remarkably like a real bird But we are unable to build a real bird that reproduces itself and behaves in all respects like a real bird Building a model aeroplane can use the same materials and construction techniques as a real aeroplane, whereas the materials and techniques of model bird construction are fundamentally different from a real bird Similarly, all models of forest ecosystems ultimately disappoint to some extent, because they fail to represent the ecosystem exactly However, just as a model bird that flies may be very useful in analysing bird flight, an ecosystem model designed to examine the impact of forest management on productivity can be very useful in helping us to understand and predict the future functioning of a forest stand under a variety of alternative management and environmental conditions

References

Aber, J.D. and J.M. Melillo. 1981. FORTNITE A computer model of organic matter and nitrogen dynamics in forest ecosystems Univ of Wisc Res Bull R3130 39 p

Brown, L.R., E. Wolfe and L. Starke. 1984. State of the World 1984 a Worldwatch Institute report on progress towards a sustainable society W W Norton & Co NY 252 p

Clark, W.C. (ed.). 1982. Carbon Dioxide Review 1982 Oxford Univ Press 469 p

Council on Environmental Quality. 1981. The Global 2000 Report to the president Blue Angel Inc Charlottesville Va 700 p

Industrial Working Party. 1982. World forest products demand and supply 1990 and 2000 Food and Agriculture Organization, UN Rome 222 p

Kane, T.T. 1983. World population data sheet Population Reference Bureau Inc 1337 Connecticut Ave NW Wash D C 20036

Kimmins, J.P. and K.A. Scoullar. 1983. FORCYTE-10 A User's Manual 2nd approximation Contract report to the CFS Ottawa 117 p

Kimmins, J.P. and K.A. Scoullar. 1984. FORCYTE-11 A flexible modelling framework with which to analyse the long-term consequences for yield, economic returns and energy efficiency of alternative forest and agro-forest crop production strategies In 5th Canadian Bioenergy R&D Seminar Proc Nat Res Council Canada 1984 p 126-130

Kimmins, J.P. and K.A. Scoullar. 1985. The role of modelling in tree nutrition research and site nutrient management *In* Bowen, G A and E K S Nambiar (eds), Nutrition of Plantation Forests Academic Press NY p 463-487

Klinka, K., W.D. van der Horst, F.C. Nuszdorfer and R.G. Harding. 1980. An ecosystematic approach to forest planning For Chron 56 97-103

Kojima, S. 1981. Biogeoclimatic ecosystem classification and its practical use in forestry J Coll Liberal Arts, Toyama Univ , Japan 14 41-75

Krajina, V.J. 1969. Ecology of forest trees in British Columbia Ecol West N Amer (Dept Bot UBC, Vancouver) 2(1) 1-147

Krajina, V.J. 1972. Ecosystem perspectives in forestry H R MacMillan Lectureship in Forestry UBC, Vancouver B C 31 p

Morrison, I.K. 1984. Acid rain A review of literature on acid deposition effects in forest ecosystems For Abstr 45 483-506

Rowe, J.S. 1961. The level-of-integration concept and ecology Ecology 42 420-427

Smith, W.H. 1985. Forest quality and air quality Forestry 83 82-92

Trimble, J. and C. Shriner. 1980. Inventory of United States forest growth models Report to the IEA Biomass Working Group, Planning Group A Environ Sci Division, Oak Ridge National Laboratory Dept of Energy

van der Tak, J., C. Haub and E. Murphy. 1979. Our population predicament a new look Population Bull 34(5) 48 p

World Bank. 1984. World Development Report 1984 Oxford University Press, Oxford 286 p

University of Toronto

The E. B. Eddy Distinguished Lecture Series

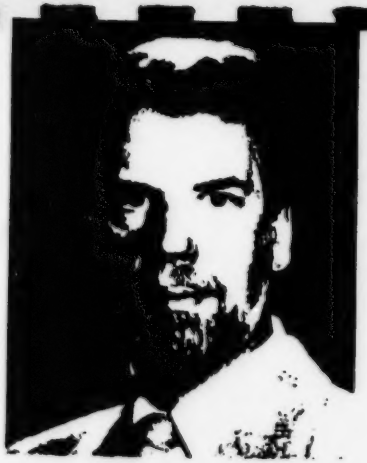
FORCYTE In Forestry: The Need for a Systems Approach In Forestry Education, Yield Prediction and Management

J. P. Kimmins

The State of Forest Research In Canada

G. L. Baskerville

November, 1986



Dr. J. P. Kimmins received his B Sc (Hons) from the University of Wales, an M Sc from the University of California and his M Phil and Ph D from Yale University

Dr Kimmins is currently Professor of Forest Ecology at the Faculty of Forestry, University of British Columbia His career at the University of British Columbia included an Assistant Professorship from 1969 to 1974 and an Associate Professorship from 1974 to 1979 Major works include a User's Manual on FORCYTE-10 in 1983 and a User's Manual on FORCYTE-11 in 1986, as well as a textbook on Forest Ecology in 1986 Dr Kimmins has made an outstanding contribution to forestry with his innovative design and development of the FORCYTE computer model FORCYTE (Forest Nutrient Cycling and Yield Trend Evaluator) is an ecologically-based forest management simulator It is currently being used and/or evaluated by thirty-one university, industry, government research and forestry divisions in eleven countries in conjunction with seventeen different tree species, forestry systems and agroforestry systems

Dr Kimmins received a Killam Leave Fellowship to Oxford University in 1975–76, a JSPS Visiting Scientist Fellowship to Kyoto University in 1982, and a IUFRO Scientific Achievement Award in 1986

FORCYTE in Forestry: The Need for a Systems Approach in Forestry Education, Yield Prediction and Management[1]

J. P. Kimmins[2]

Abstract

One of the unique and often problematical features of forestry is its long time scale relative to that of most other human economic endeavours Tree crop production activities generally extend far into the future, and successful sustained management of forest resources requires accurate predictions of future forest production Such predictions have always been difficult, but they are becoming more so as the rate of change in forest management becomes greater than the rate at which we can adjust our traditional tools of yield prediction Forestry is experiencing the same type of "future shock" that other aspects of human society have been facing for the past several decades New yield prediction tools are needed that can accommodate the types of changes that forestry will probably undergo over the next rotation

Many of the problems that beset forestry can be related to variations in the time and space scales at which different levels of forestry activity take place These scale differences constitute barriers to the information exchange between different levels of forestry that is so necessary for successful forest management Mechanisms are needed by which to promote and facilitate information transfer between forest research, stand management, whole-forest management, and provincial and national forest policy

The adoption of a systems approach in all aspects of forest land management would facilitate both yield prediction and between-level information transfer Such an approach is particularly important in the following three types of forestry activity: forestry education,

[1]Presented at the Faculty of Forestry, University of Toronto, 05 November 1986, lecture supported by funding provided to the Faculty by E B Eddy Forest Products Limited

[2]Professor, Forest Ecology, Faculty of Forestry, University of British Columbia, Vancouver British Columbia, Canada

stand management, and whole-forest management. The need for and nature of the systems approach in these three activities is explored, and FORCYTE, an ecosystem-level forest management simulator, is described as an example of the type of analytical tool that can assist in developing the systems approach. Models such as FORCYTE can play a very useful role in forestry education, can improve stand-level yield prediction, and can assist in bridging the information gaps between the various levels of research, stand management, and whole-forest management.

Introduction

The production of most tree crops involves space and time scales that are much larger than those of most other human economic endeavours. The magnitude of these scales gives forestry a unique character and contributes to a variety of problems that can impede the attainment of management objectives. For example, the long time scale makes it very difficult to answer questions such as:

- Which species should be planted to supply the markets that will exist at the end of the rotation?
- What impact will site preparation by broadcast slashburning have on tree size, quality, value and volume-per-hectare at final crop harvest?
- What are the consequences of regeneration delay for the volume and value of the final crop, and can stand management practices applied later in the rotation compensate for the delay?
- Can site degradation caused by harvesting and/or site preparation be rendered acceptable both environmentally and economically by the end of the rotation by means of subsequent ameliorative activities?

Forest managers are continually facing stand-level questions like these: questions that require believable answers if we are to make wise management and investment decisions. Such stand-level questions are difficult to answer because of their complexity. complexity that results from the many different factors that are involved because of the long time and large space scales. Answering such questions requires a systems approach[1] in order to deal with this complexity.

Similarly, the combination of long time scale and large space

[1]System (in the sense of forestry): a set or arrangement of activities so related or connected as to form a single, unified whole. Systems approach: the analysis of individual objects or activities in the context of the overall system of which they are a part.

Systems approach in forestry: the analysis of any forestry activity in terms of the level of forestry at which the activity is conducted, and in terms of the relationship of that activity to both higher and lower levels of forest management activity (cf. Figures 1 and 2, and Table 1).

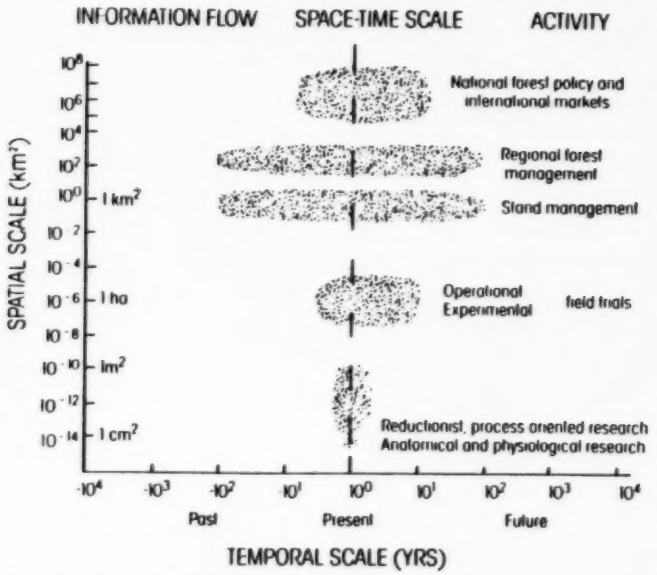


Figure 1 *Variation in the temporal and spatial scales associated with different levels of forestry activity, from reductionist forest research up to national forest policy (based on Baskerville 1985, used with permission)*

scale makes it difficult to answer such whole-forest questions as: What combination of stand management strategies, varied by site and location, will optimize either volume or value production over an entire forest estate or region? Only by examining such questions in terms of both stand and whole-forest systems can optimum solutions to such questions be obtained.

Forestry involves a hierarchy of levels of activity that vary in their time and space scales (Figure 1). Planning in forestry, whether it be at the provincial or national policy level, the regional timber supply (or whole-forest) level, the stand management level or the individual management activity level, requires that foresters are able to perceive how activities and decisions at any one level relate to activities and decisions at other levels (Figure 2). Foresters must understand how the different stand management activity systems (and the components thereof) relate to each other, and how they combine to form the overall stand-level tree crop production system. They must also understand the role of stand management in the hierarchy of regional and national forestry systems, and not be so preoccupied with stand-level considerations that they lose sight of whole-forest level concerns. On the other hand, they must also understand that many whole-forest problems, such as age-class gaps in the whole-forest structure, may persist or recur in the future if stand-level

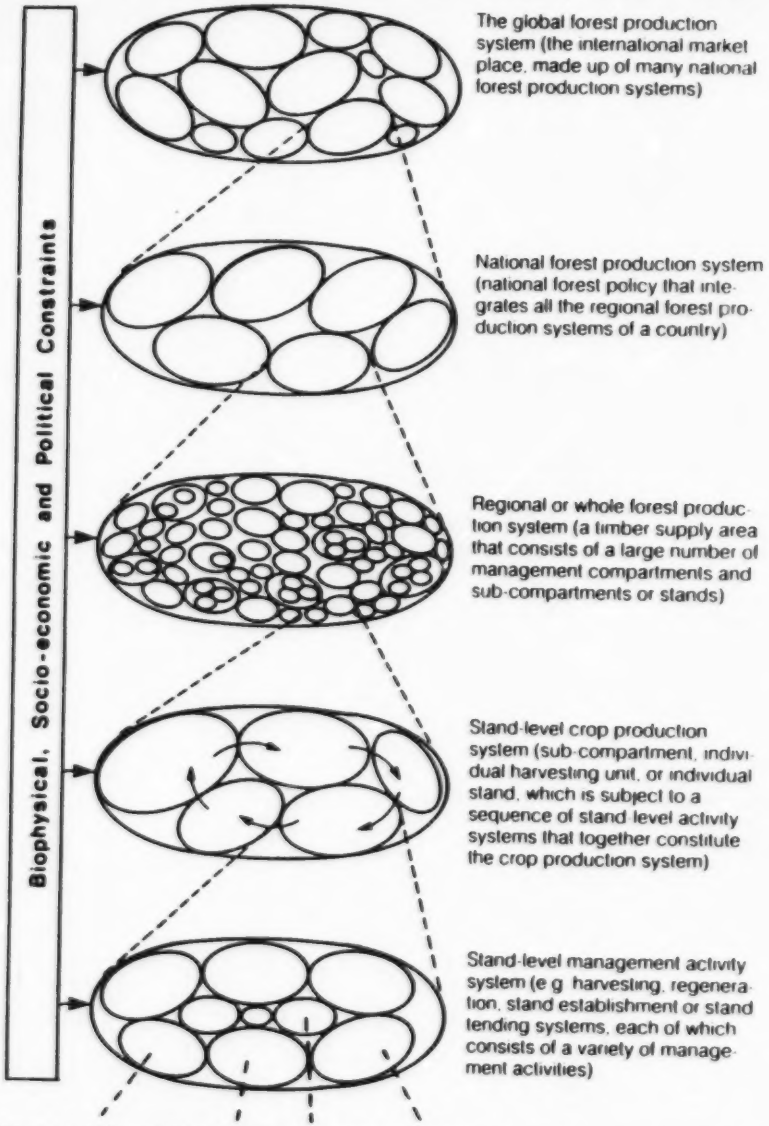

Biophysical, Socio-economic and Political Constraints
The global forest production system (the international market place, made up of many national forest production systems)
National forest production system (national forest policy that integrates all the regional forest production systems of a country)
Regional or whole forest production system (a timber supply area that consists of a large number of management compartments and sub-compartments or stands)
Stand-level crop production system (sub-compartment, individual harvesting unit, or individual stand, which is subject to a sequence of stand level activity systems that together constitute the crop production system)
Stand-level management activity system (e g harvesting, regeneration, stand establishment or stand tending systems, each of which consists of a variety of management activities)
Various activities within an activity system (e g seed collection, nursery production, site preparation and planting are some of the activities within a regeneration system)

Figure 2 *The hierarchical nature of forestry management systems. Each level includes numerous systems of the next lower level in the hierarchy. Each level is subject to a variety of biophysical, socio-economic and political restraints*

management is not successful. In addition, foresters at all levels must be aware of the biophysical, socio-economic and political constraints that must be considered if the forestry enterprise is to be successful; they must be able to integrate tree crop production with the management of other resource values.

The fact that many forest resource managers I have met have not been able to perceive adequately either the integrated hierarchical systems nature of forestry, or the diversity of resource values and variety of constraints that act at various different levels (Figure 2) lies, I believe, behind many of the continuing difficulties that face the forestry sector. An analytical, reductionist approach to forestry education and management may be the ultimate cause of this inability, and thus of many forest management problems. The solution to these problems lies, I believe, in the adoption of a systems approach to many aspects of forestry.

The objective of this paper is to examine three types of forestry activity in which the failure to adopt a systems approach can be one of the major constraints on improvement in the success of forest management:

1. *The education of foresters.* This is the foundation on which future philosophies, attitudes and approaches to forestry are built. The tendency towards a reductionist, piecemeal approach to education in general, and to forestry education in particular, contributes, I believe, towards a reductionist, piecemeal approach to forestry.
2. *Stand management.* This is the level of forestry at which silviculture is practised, and it is the basis for whole-forest management. It should involve an integrated system of management activities applied to a landscape unit over a rotation. Unfortunately, it is often approached in terms of a series of relatively unconnected site and stand treatments considered in terms of managing populations of trees, rather than of whole ecosystems.
3. *Whole-forest management.* Calculation of annual allowable cuts, the geographical distribution of the cut, and the age-class structure and species composition of the population of stands are important questions that transcend the individual stand level and largely determine the temporal pattern of timber supply, quality and value. However, preoccupied with these and other regional management concerns, a forester may lose sight of the stand-level aspects of management, and of the fact that the aggregate of what happens at the stand level determines in large part what will happen at the whole-forest level in the future.

In all three of these examples, a systems philosophy and approach can contribute significantly to the attainment of the goals of the activity at that level and of forestry in general. The paper will

conclude with an examination of how one example of the systems approach (FORCYTE) can be used to facilitate activities at these three levels

A Systems Approach to Professional Education in Forestry

Almost the entire education system of western civilization encourages reductionism. Knowledge is categorized as being "Science" or "Arts", scientific knowledge as being biological or abiological, biological science as being botany, zoology, microbiology, etc., and botany as being genetics, physiology, morphology, etc., and so on.

As a consequence of reductionism, the curriculum and the component courses thereof in primary, secondary, and post-secondary education tend, with notable exceptions, to become increasingly narrow and specialized as a student proceeds through the system. In many respects this is both necessary and desirable. As the body of knowledge expands it becomes increasingly necessary to limit the scope of many programs and courses, and for students to specialize if they are to be able to grasp all of the current wisdom in their chosen field. Without such specialization, there would have been slower progress in our understanding of the individual components and process of the world we live in, and of the universe around us.

Recognizing the benefits of reductionism, society has rewarded it with diplomas, degrees and Nobel prizes, and until very recently there has been a strong tendency for greater prestige and honour to be given to reductionist, analytical activities and achievements than to broadly-based, synthesis-type activities. However, many of the problems that beset society cannot be solved by a narrow analytical approach. Management of many important social and economic activities requires a broad, synthesis-type approach. Forestry is a good example of such an activity.

It is the product of this pro-reductionist educational environment that is delivered into the hands of forestry educators. In general, students entering forestry schools are better prepared to memorize, analyse and understand narrow, relatively homogeneous packages of knowledge than to synthesize information from divergent subject areas. Because of their analytical training, incoming students tend to be better equipped to think about and analyse individual forestry activities than to perceive how the entire system of management activities is integrated over a rotation. They often find it easier to understand the growth of an individual tree than the temporal development of a stand, or the growth of an individual stand than to appreciate how the growth of all the stands in an entire forest timber supply area combine to produce a sustained supply of various goods and services from the forest.

Recognition of this tendency should have an important influence on the design of forestry curricula. Emphasis should be given throughout the educational experience to the fact that forestry is a set of nested systems, from individual stand management activities, through stand and whole-forest management, to provincial and national forest policy and the international forestry marketplace. The curriculum should begin with an overview course that introduces the entire hierarchy of forestry activities. This would not only "sow the seed" of the systems approach, it would also identify the knowledge and tools that are needed by foresters to understand and manage the various systems depicted in Figure 2. This overview course should be accompanied, where necessary, by courses that strengthen the student in the *basic knowledge* of those sciences, communication

Table 1 Suggested stages in a basic professional forestry education. The four major levels shown do not necessarily imply four years of study. Whether or not all the major topics would be covered in four years would depend on the depth of treatment.

Stage of Education	Major Topics
4 Whole forest and higher levels of forest management. Integration of all levels of the forestry enterprise into an overall management system	Whole forest management planning. Wood products manufacturing and marketing. Forest policy. National and international forestry. Research. People management. Communication skills. Computers in forest management. Ethics and professionalism. Special applications (urban, agro- and energy forestry)
3 Methods and tools of, and constraints on, stand management	Silviculture, pathology, entomology and fire. Wildlife, watersheds, fish, range and recreation. Stand management planning tools. Engineering. Forest economics
2 Technical foundations of forestry	Earth, atmospheric, and ecological sciences. Dendrology, Wood Science. Silvics and Genetics. Biometrics and Computer Science. Photogrammetry and Mensuration
1 Introduction to forestry systems and the basic knowledge on which successful forestry is founded	Forestry systems: an overview of forestry. Basic sciences. Mathematics. Economics, philosophy and psychology. Communication skills
BASIC KNOWLEDGE OF SCIENCES, HUMANITIES AND COMMUNICATIONS SKILLS GAINED AT SECONDARY SCHOOL	

skills and humanities that are needed in the successful management of forest resources (Table 1). This introductory period should be followed by a treatment of the *technical foundations* of forestry, leading to a presentation of the *methods and tools* of stand management. The professional forestry curriculum should conclude with an emphasis on the systems approach through a study of whole-forest, provincial, national and international levels of management, and on the interaction between forestry systems and the social and economic systems that create the overall environment within which forestry is conducted (Figure 3).

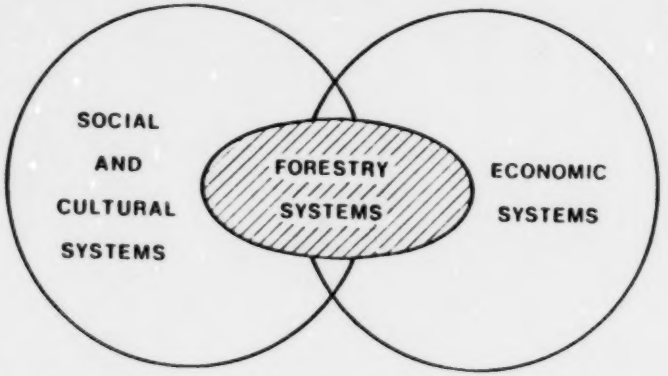


Figure 3 *Forestry systems are closely linked to social and economic systems which create the environment within which the biophysical stand and whole-forest systems are managed.*

The variety of topics suggested in Table 1 places constraints on the number of elective and specialized courses that can be included in a basic undergraduate degree in forestry *if* the time requirement for the degree is to be kept to a minimum. I believe that in the trade-off between, 1) the freedom to specialize, and 2) the need to integrate all aspects of forestry into management systems, to develop the tools of synthesis, and to give students first-hand experience of the planning and analysis of entire forest systems, the latter should be favoured. The benefits of specializing at the undergraduate level must be balanced against the need for foresters to be trained in synthesis and methods of dealing with complex, multifactorial problems and systems. The joys of specialization should probably be reserved for the smaller number of specialists who will assist the larger numbers of generalist foresters. Advanced courses to prepare students for more specialized job opportunities should be offered at the post-graduate degree, diploma or continuing education level.

A Systems Approach to Stand Management

There are two major reasons why stand management should be approached from a systems point of view: 1) the need to consider stand management as a system in order to maximize value production, and 2) the need to adopt an ecosystem or landscape view of stand management in order to improve the forester's ability to predict the yield consequences and other outcomes of alternative management practices. The latter is necessary if environmentally and economically wise choices are to be made between alternative management strategies.

1 *Stand management as a system*

Even-aged stand management involves the crop rotation cycle from site preparation, through regeneration, early stand tending (including vegetation management), stocking control and fertilization, to intermediate and final harvesting, with appropriate activities to protect against fire, insects and diseases. Each of the silvicultural activities in the stand management system must be justified, not only by its short-term and medium-term results, but also by its effect on the yield and economics of the final crop. It must be evaluated in terms of its contribution to the production of the desired tree size, wood quality, and biomass (volume) per hectare at the lowest cost in the shortest period of time. In other words, each silvicultural activity must be justified in terms of maximizing the present net value of the crop, consistent with a variety of other management considerations, including long term sustainability of production, non-timber resource values, and regional-level management considerations. Consequently, each cultural practice can only be fully evaluated when considered as a part of an overall stand management system. I will present some examples.

A Broadcast slashburning is a widely used site preparation technique which, when used correctly, can offer many tangible benefits, including ease of regeneration, control of pests and pathogens, temporary reduction of fire hazard and weed competition, and improvement of crop tree growth through effects on soil temperature and soil chemistry. However, care is required in its use because it is a powerful tool, and if applied in the wrong place, in the wrong manner and/or at the wrong time, it can adversely affect such things as soil stability, moisture status, and soil fertility. As a result of these adverse impacts, slashburning practices have often been criticized.

Evaluations of slashburning have generally been based on its short-term effects, whether these are negative or positive, and it is clear that an evaluation conducted over an entire rotation could, in some cases, lead to a different conclusion. There are cases

where a short to medium-term negative impact on soil moisture and fertility (especially loss of nitrogen) may be justified by the end of the rotation. A fire-related reduction in regeneration delay and an improvement in stocking, when combined with fertilization to replace the lost nutrients and to promote the rebuilding of soil organic matter, may convert the short-term adverse impact into an acceptable and even desirable component of a rotation-length stand management system. Slashburning on infertile, dry sites is generally thought to have adverse long-term effects on site productivity, but short-term evaluations of adverse impacts made in isolation from the entire crop production system may lead one to reach incorrect conclusions about the rotation-length consequences of these initial impacts. Similarly, short-term beneficial effects of slashburning can be followed by negative effects by mid-rotation, with an overall negative impact by the end of the rotation.

B. Invasion of west coast clearcuts by red alder (*Alnus rubra* Bong.) can severely inhibit the regeneration and/or the early growth of shade-intolerant coniferous species such as Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco). Eradication of the alder by fire, chemical, or mechanical means is considered by most foresters to be desirable in terms of coniferous crop establishment and early stand growth. However, early elimination of red alder may have negative effects over a rotation-length time scale. Historically, red alder has played an important role in secondary plant succession following disturbance of some types of coastal forest ecosystem by fire, windblow or logging. During the red alder phase, large amounts of nitrogen are fixed symbiotically by the alder and incorporated into the soil providing the nitrogen-rich sites on which Douglas-fir can grow to a height of as much as 70 m in 100 years. Although strong empirical evidence is still lacking, theoretical considerations and some limited field evidence suggest that successful elimination of alder will result in the requirement for significant fertilizer inputs of nitrogen through the rotation if the productivity exhibited in the original unmanaged stands on these sites is to be maintained. Given the cost of alder eradication and of nitrogen fertilization, and considering the risk of reduced crop growth, acceptance of some level of alder competition for part of the rotation may result in a greater net present worth than would successful early alder eradication programs. Use of crop species sequences, such as alternating Douglas-fir and alder mono-cultures, may be economically superior to Douglas-fir-only silvicultural strategies.

Economic forestry favours maximizing present net value, subject to a variety of management constraints. Maximum present net value will only be achieved if entire, rotation-length stand

management systems are considered, so that the right silviculture is applied at the right time, in the right places and in the right amounts (Baskerville 1986).

2. *Systems approach to yield prediction in stand management*

The most fundamental tenet of science is that all things can be explained; for every event or condition there is an identifiable set of antecedent determinants. This is the Principle of Determinism. The complexity of determinism varies from low (causal determinism: a single "cause" that explains an event) to high (statistical determinism, where events have probabilities of occurrence and cannot be predicted with certainty because of the large number of determinants).

An important corollary of this principle is that as the complexity of determinism (i.e. number of antecedents) increases, the ability to accurately predict future events decreases (Figure 4). On average, with all antecedents contributing equally, the success at predicting future events or conditions in a complex system will decrease exponentially as the number of antecedents not accounted for, explained or understood, increases (Figure 5). This suggests that we should approach stand management from an ecosystem point of view, since only in that way are all antecedents accounted for

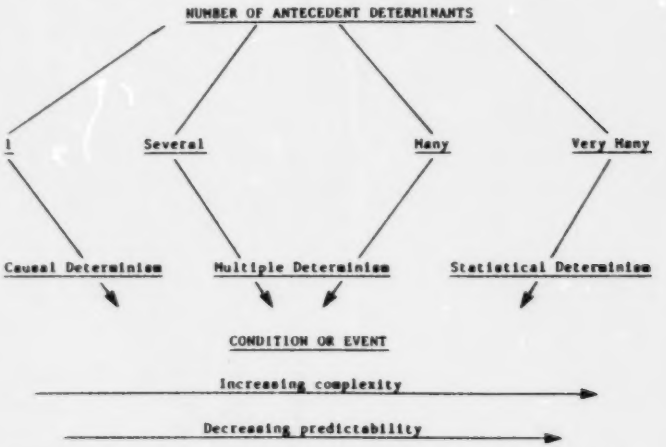


Figure 4 *Diagrammatic representation of the Principle of Determinism, which states that all conditions and/or events are associated with a set of antecedent determinants. There is a large variation in the number of antecedent determinants that can be associated with a condition or event, from a single antecedent determinant (the cause) to some very large number. This results in three types of events/conditions: those that are causally determined, those that are multiply determined, and those that are statistically determined. The importance of this principle for resource management lies in the inverse relationship between the complexity of the determinism and the predictability of the condition or event.*

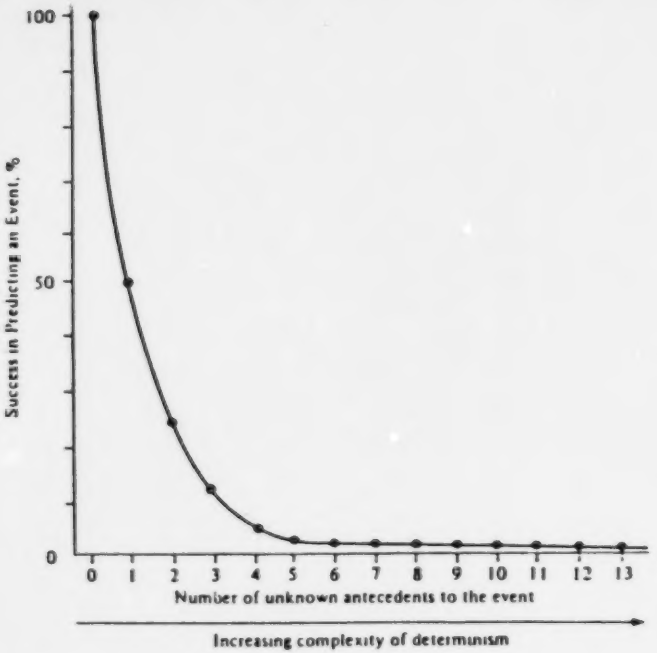

100
50
0
Success in Predicting an Event, %
0 1 2 3 4 5 6 7 8 9 10 11 12 13
Number of unknown antecedents to the event
Increasing complexity of determinism

Figure 5. *Relationship between the predictability of a condition/event and the complexity of its determinism*

All biological systems can be ranked according to their level of complexity, from cells up to ecosystems. As a general rule, *understanding* an ecosystem phenomenon such as forest growth (an individual, population or community event) requires knowledge of processes at lower levels of biological organization (organs, cells; Figure 6). In contrast, *prediction* of future forest growth must be done at the ecosystem level, because only at that level are all the major antecedent determinants of growth identified, implicitly or explicitly. Only by considering events in terms of the next true level of biological *integration* above the level of interest will one gain the desired powers of prediction (Figure 7).

Accurate prediction of future stand growth is the cornerstone of good management planning. Traditionally, such predictions have been based on the *historical bioassay* type of model: yield tables, volume/age equations, or mensurational computer models (Kimmins 1985). Such models have served foresters well because they are implicitly ecosystem-level models. Forest growth integrates the effects of all the growth-determining factors of the ecosystem. However, lacking any explicit representation of ecological and

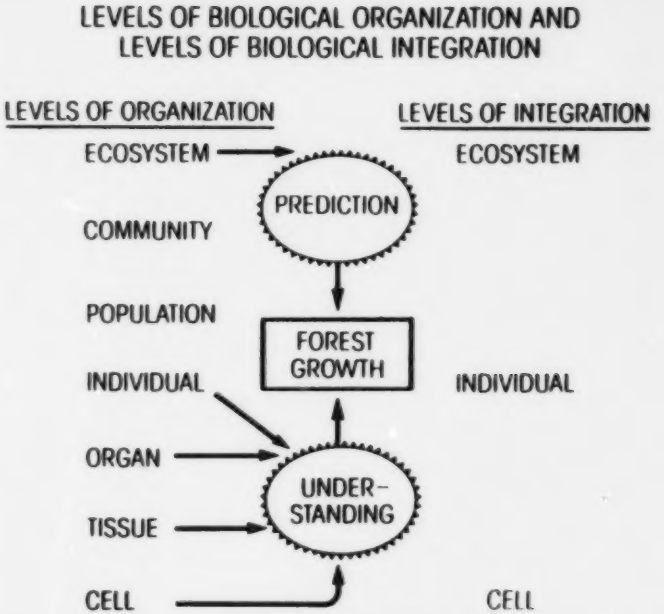
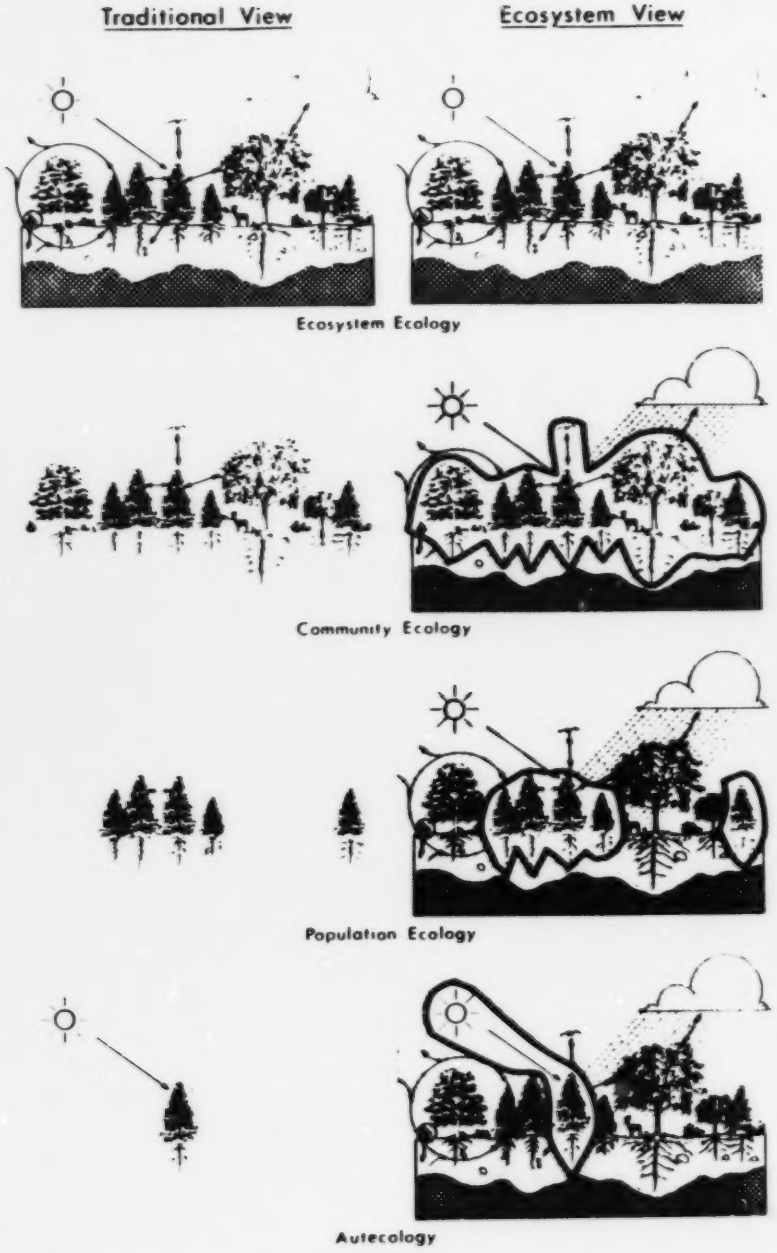


Figure 6. *Levels of biological organization and levels of biological integration relationships to understanding and predicting forest growth (based on Rowe 1961). Understanding stand growth (a population/individual level phenomenon) requires knowledge of photosynthesis and resource allocation at the cellular, tissue, organ and whole individual level. Predicting stand growth requires an ecosystem approach because only at that level are all the major antecedent determinants of forest growth over a rotation accounted for.*

physiological processes, historical bioassay models are inflexible and are unable to make accurate predictions under significantly altered future management (and hence growth) conditions. The alternative of using purely process simulation models has not proven to be satisfactory because such models have not yet been able to represent enough of the complexity of forest ecosystems to make accurate predictions over rotation-length time periods. Process models have tended to be individual, population or community models rather than ecosystem-level models. In response to the deficiencies of these two approaches, hybrid historical bioassay-process models have been developed that combine the implicit ecosystem-level of complexity of historical bioassay models with some of the flexibility of process models. FORCYTE[1], which will be described later, is an example of such a hybrid stand model.

[1] *Forest nutrient Cycling and Yield Trend Evaluator*



From the point of view of both the evaluation of individual stand management treatments and the prediction of future yield, one can conclude that stand management should be firmly based on a systems (including ecosystems) approach

Systems Approach to the Higher Levels of Forest Management

The application of the systems approach is just as important at the whole-forest, national forestry, and international forestry levels as it is in forestry education and stand management

It is very easy for foresters to become preoccupied with the stand level of management, because this is the level at which silvicultural activities are conducted However, many of the important questions in forestry involve things such as raw material supplies to mills, whole drainage basin watershed and wildlife considerations, and national and international markets: questions that transcend the stand level and cannot be answered on the basis of knowledge of stand-level or lower systems alone In regional or whole-forest management, stand-level decisions may be subjugated to the goals of optimizing investments over an entire industrial or government holding, and to ensuring a desired level and continuity of supply of wood or other forest products Biophysically sub-optimal stand-level management decisions may be made deliberately on some sites in order to optimize value and volume production on other sites, or to solve short-term supply or economic problems Similarly, fluctuating demands for wood products, for product qualities, and for species mixtures generated by regional, national and international markets may result in alterations in stand, as well as in whole-forest management strategies[1]

Selection of optimum strategies at any one of the management system levels depicted in Figure 2 should be made on the basis of an analysis of the management system at each level, *and* of the interactions between levels Successful strategy selection is much more likely if the strategies are examined in the context of a set of

[1]These and other regional forest management issues relevant to Ontario are discussed in Baskerville (1986)

Figure 7. *"Traditional" and "Ecosystem" views of the subdivisions of ecology In the traditional view, ecosystems are disaggregated into biotic communities (biotic community is the focus of attention), biotic communities are disaggregated into populations (individual species populations are the focus of attention), populations are disaggregated into individuals (the individual and its physiology are the focus of attention) In the ecosystem view, the attention may focus on any one of these levels of biological organization, but always in the context of the ecosystem framework in which the level exists The ecosystem view ensures that all major determinants of events or conditions are considered, no matter what the focus of attention Prediction of future events at the individual, population and community levels is likely to be much more successful using the "ecosystem view" than the "traditional view"*

nested management systems, and if there is appropriate flow of information between the different levels

Unfortunately, while the interchange of knowledge between the different levels of forestry activity may sound simple, in reality it is not Because of variations in temporal and spatial scales between the different levels (Figure 1), information flow between them may be very difficult The volumes of reductionist forest research which fill forestry libraries around the world may increase our knowledge and understanding of the processes that occur in various forestry systems, be they biological, physical, silvicultural or socio-economic processes However, much of the content of these libraries is of little practical value to stand and regional managers because the information is based on studies conducted at such widely different time and space scales On its own, much of the forest research literature may be of relatively little help in predicting the rotation-scale consequences of alternative stand treatments because the research relates to levels of biological organization far below that of the ecosystem, because it considers individual components of management systems out of the context of the overall system, and/or because it is concerned with inappropriate time and space scales The gaps between the time and space scales of physiological and soil process research, stand management, and whole-forest

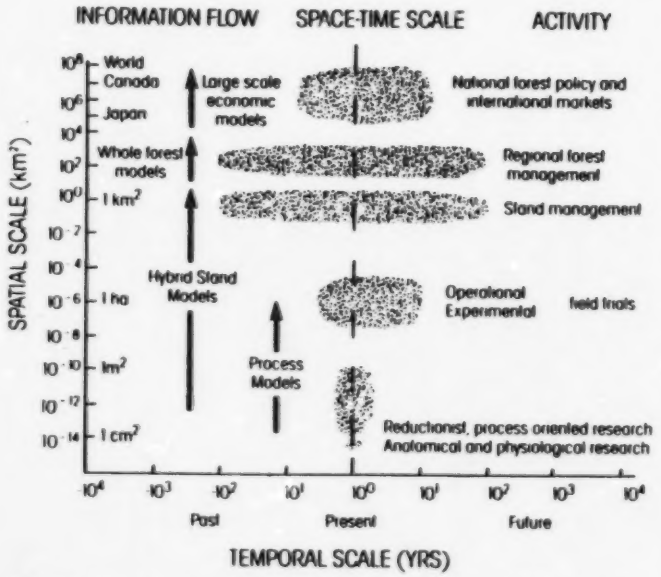


Figure 8 *The role of models in bridging the space and time scale gaps between the different levels of forest management activity (c f Figure 1)*

management may be too great to permit easy transfer and practical application of the research results However, this problem can be significantly reduced by use of the system analysis tool of computer simulation modelling to bridge the time and space scale differences (Figure 8)

Process simulation models can facilitate the exchange of knowledge between the most detailed reductionist process research and field trials Hybrid stand models (e g FORCYTE) can help to bridge the gap between either field plot or process research and stand level management Hybrid models can also be used to produce simulated managed stand yield tables These can be used as input data for whole-forest models, thereby improving our predictions concerning annual allowable cuts and yield flows under a variety of possible future management scenarios for which we do not yet have empirical evidence Hybrid models thus link reductionist, process-level research with stand-level management, and facilitate the linkage of stand-level knowledge with regional and national forest policies and strategies They can improve on the projections of models like OWOSFOP (Baskerville 1986) by creating a more ecologically credible projection of the stand level consequences of various silvicultural activities and strategies

FORCYTE: A Hybrid Stand Simulation Model for the Analysis of Long-term Consequences of Alternative Stand Management Systems

1 *Introduction*

FORCYTE is a hybrid between the historical bioassay and the process simulation types of yield model (Kimmins 1985, 1986) It is designed to examine the consequences of a wide range of alternative stand management systems for yield, biomass production, nutrient and organic matter budgets and dynamics, stand-level economics, and the energy-efficiency of stand management Earlier versions (up to and including FORCYTE-10) focussed mainly on questions of site nutrient depletion and nutritional regulation of yield The current version (FORCYTE-11) adds canopy architecture and light profiles as determinants of growth, competition for light between species, and the size of individual trees It is a hybrid model in three ways a hybrid between a historical bioassay and a process model, a hybrid nutrient-light process model, and a hybrid stand-individual tree growth model FORCYTE-12 will add temperature and moisture considerations, as well as an improved representation of soil processes

The philosophical approach adopted in FORCYTE is to take a traditional historical bioassay yield predictor, which is considered to be the most believable and practically useful yield prediction tool where future growth conditions remain unchanged, and to add to it

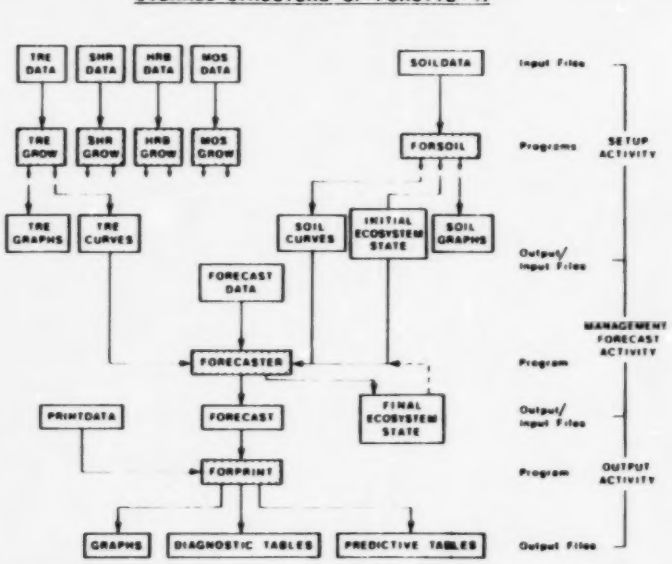


Figure 9 *Flow chart of input files, programs and output files of FORCYTE-11 showing the modular nature of the model. FORCYTE-11 can be customized for management systems that vary from very simple to very complex, and from conventional forestry, to agro-forestry, agriculture and land reclamation*

sufficient process simulation to give it the flexibility needed to predict yield under a variety of specific future growth conditions. Not all of the important growth-determining factors are significantly altered by changing the stand management system. Regional climate, topography and soil texture, for example, are important but are not normally altered as stand management changes. Canopy light conditions and soil nutrient availability, on the other hand, are very susceptible to change. Soil moisture is less susceptible to change, but is an important growth-limiting resource, and thus plays an important role in determining between-species competition, especially in dry climates and on dry sites. Consequently, a process simulation of the moisture factor should be included.

FORCYTE-11 is a modelling framework, rather than a single model. It is modular in makeup, and consists of a series of sequential stages (Figure 9). This enables the user to simulate management systems varying greatly in complexity. If desired, it permits a high degree of explicit representation of the inherent complexity of ecosystems and their management, but without any one program or file becoming too big to be useful. It also reduces the cost of, and/or the computer requirements for running the management simulator,

since many of the calculations needed in every management simulation are performed in an initial set of programs and the results transferred to the management simulator. It can be implemented on the present generation of microcomputers if they are equipped with a high-speed co-processor, or on any "main-frame" computer.[1]

FORCYTE-11 consists of two major activities: the "setup" activity and the management forecast activity. In the former, empirical data on plant growth, size and chemistry, on shading beneath the canopy and the photo-synthetic response to shading, and on a variety of other plant biomass parameters, are used to obtain an empirically-based measure of foliage production efficiency (biomass produced per kilogram of foliage nitrogen, corrected for shading), and the allocation of net growth to different biomass components and between different individual trees. Similarly, a soil setup program using empirical data on certain soil processes and parameters is used to establish temporal patterns of a variety of soil processes. The output of these setup programs, which simply reflect the input data, is then combined in a simulation of the management of the ecosystem in order to predict the consequences of the simulated management system for a variety of management, ecological, economic and energy parameters over one to several rotations. A third activity is concerned with presentation and analysis of data output. The output can also be directed to a variety of existing data management and graphical packages such as SYMPHONY (or LOTUS-1-2-3).

Table 2 lists the management options that will be available in the full working version of FORCYTE-11, while Figure 10 summarizes the components and processes that are represented in the model. The user may employ as few or as many of the management options as desired, and throughout the model the user has the option of switching off the simulation of processes which are either inappropriate for a particular application, or for which there is inadequate calibration data. Through the input data, the user can control the rates of processes, and can alter many of the assumptions in the model.

2 Use of hybrid models like FORCYTE in forestry education and whole-forest management, and as a stand-level research tool

FORCYTE is presently being used as an educational and/or research tool at 19 universities in eight countries. It has been used in courses on forest ecology, forest soils, and silviculture to demonstrate the linkages between different ecosystem processes, and the effects of different stand management systems thereon. It has proven to be

[1] For further information on the availability of FORCYTE and its hardware requirements contact the author.

Table 2 *FORCYTE 11 management options and major categories of output*

Management Options	
Site Preparation Systems	ploughing scarification windrowing broadcast burn pile and burn
Regeneration Systems	planting (trees of any age, size and root/shoot ratio) natural regeneration from seed after clearcutting vegetative regeneration (coppice sprouting or root suckering) regeneration delay single crop species or mixtures of up to 3 crop species
Stand Establishment Systems	control of competing vegetation
Stand Tending Systems	stocking control (spacing, pre commercial thinning) species control fertilization (up to 5 nutrients in broadcast spot or band fertilization) pruning of dead and/or live branches under-burning of stands
Harvesting Systems	commercial thinning (high, low, random or other types) final harvest (clearcut) rotation length utilization level slash harvesting forest floor harvest (litter raking)
Wildlife Systems	wildlife (or livestock) browsing of trees or minor vegetation. Effect of stand management on biomass of browse species
Other Management Aspects	wildfire (crown, surface, ground, or combination) insect defoliation soil compaction and/or erosion agro-forestry alternating crop sequences (eg. alder-Douglas-fir-alder sequences) ability to simulate changing management strategies over time, management system changing between rotations
Output	Graphs depicting biomass accumulation of trees and minor vegetation over time, individual tree size, soil processes, organic matter and nutrient dynamics, canopy functions and tree mortality Tables summarizing 1) biomass production, yield, slash production, and change in stand organic matter and nutrient inventories over the crop production cycle, 2) ecosystem production and nutrient budgets, 3) stand economics, 4) energy efficiency of management Effects of thinning and pruning on stemwood volume by piece size, sapwood/heartwood, and knottiness

particularly helpful in permitting students to grasp the long-term economic and biological consequences of individual stand management activities, and of the interaction between various silvicultural activities undertaken at different times during the crop production cycle. In short, it facilitates a systems view of stand-level forest management, and an understanding of the consequences of individual activities and systems of activities for the yield and the value of the crop at the end of the rotation. There can be little question that one of the major values of models like FORCYTE is in the education of undergraduate, post-graduate, professional and technical foresters.

Models like FORCYTE can be a very useful management gaming tool with which to rank a number of alternative stand management systems. Although appropriate empirical evidence from field trials *will always* be preferable to the predictions of a computer model, foresters will rarely have such empirical evidence of rotation-length effects of the variety of management systems that they would like to choose between. In the absence of such data, a hybrid simulation model can provide a significant improvement over the traditional methodology for ranking management choices.

Whole-forest models have traditionally relied on yield tables as the basis for their allowable cut calculations and economic forecasts. Where the yield tables are of the historical bioassay type, whole-forest models will produce very questionable yield predictions for future management systems about which empirical evidence does not yet exist. Sophisticated economic analysis in whole-forest models cannot be justified if the predictors of tree growth and production sustainability used as the basis for the predictions are biologically/ecologically unrealistic. In such cases, simulated managed stand yield tables (based initially on the historical bioassay yield models, but modified by some process simulation) can be prepared by a model such as FORCYTE and used as the input to whole-forest models.

Another important area of application of hybrid stand models is in forestry research. Models can be used to test hypotheses that cannot be tested by conventional field experimentation because of the time, space and/or financial requirements of such tests. They

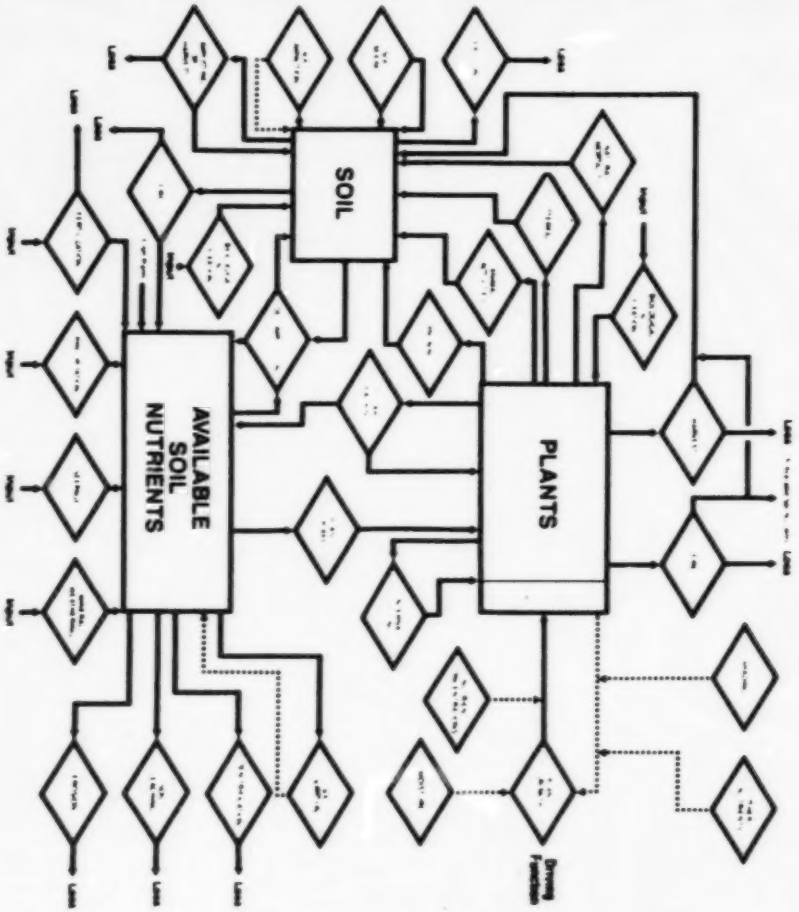


Figure 10 *Flow chart of the major components and processes represented in FORCYTE 11. A wide variety of processes can be represented, but the model can be simplified by omitting many of these processes if lack of calibration data or the desires of the user require such simplification*

can also be used to generate hypotheses that can be tested in field trials or in reductionist experimental studies. The following are some examples of how FORCYTE has been used in this respect:

(a) Use of FORCYTE-10 to simulate western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) stands in Oregon revealed that when the model was used with field data on litter and humus decomposition rates, the model would not build up the depth of forest floor that was observed in the field. Use of decomposition rates that produced a realistic forest floor accumulation provided insufficient mineralized nitrogen to allow the trees to grow realistically. This led to the realization that infrequent events (in this case catastrophic windthrow every two or three centuries) can play a major role in determining the long-term characteristics of an unmanaged ecosystem. When periodic windthrow was simulated, the model performed reasonably realistically with respect to both tree growth and forest floor accumulation (Sachs 1983).

(b) Inspection of graphical output of FORCYTE-10 calibrated for Douglas-fir on Vancouver Island suggested that the model was predicting too much loss of nitrogen (nitrate-N) by soil leaching following clear-cutting. This meant that either the model's prediction of leaching was very inaccurate (because of poor calibration data, incorrect assumptions, and/or a poor representation of soil nitrogen processes in the model), or our understanding of post-clearcutting nitrogen dynamics in the ecosystems was wrong, or both. Field studies (Martin 1985) suggested the latter. Experimental evidence implicated biological denitrification as the major post-clearcutting sink for nitrogen in the humid west coast ecosystems that were studied, in spite of the current wisdom at the start of the study that denitrification should be unimportant in the study area ecosystems. FORCYTE-10 predicts leaching of nitrate-N, but not denitrification. The model's prediction of the *disappearance* of nitrate was reasonable; it simply failed to explain the disappearance pathways adequately, and thereby revealed an incorrect understanding of one of the important processes in some west coast forests.

(c) Application of FORCYTE-10 to white spruce (*Picea glauca* (Moench) Voss) in central Alaska required a value for the rate of decomposition of humus after clearcutting. Lacking any such empirically measured value, Yarie (1986) ran the model with a range of values and identified a rate value that made the model's predictions of forest growth reasonable. Subsequent measurement of the effect of clearcutting on humus decomposition rate yielded a value close to that obtained by gaming with the model. Thus, models like FORCYTE can be used to estimate parameters that may be difficult to measure directly, or for which no empirical measurement exists.

These and other examples show that even though hybrid computer simulation models are always imperfect representations of reality, they do have significant value for research at the ecosystem and stand levels of forestry. Detailed process models may be more useful than hybrid models for research at the process level.

Conclusions

As the human population pressure on forests continues to increase, more production will be expected from less land. This will require that foresters become more successful in their management of forests, and that management at the stand level is intensified.

Improving the success of management requires that foresters have a better understanding of how ecosystems work, and that they think and plan stand management in terms of entire management systems. The correct choice between alternative stand management strategies will require an improved ability to predict the yield and economic consequences of the different strategies over the entire rotation, and this will require an ecosystem approach to yield and economic predictions. Improvement in management also requires that there be a better flow of information between the different levels of forestry activity and that foresters clearly identify the inter-relationships between stand-level and whole-forest management, and between regional forest management and the international marketplace.

The use of a systems approach can assist in all these matters. Ensuring through education that foresters have a systems concept of the biophysical and socio-economic aspects of forestry, and the use of computer simulation models at various levels of forest management are two important steps that must be taken. This in no way suggests that these approaches should displace other methods of improving the success of management, such as ecological site classification. Nor does it imply that models like FORCYTE should displace traditional yield predictors: they merely extend their abilities. To meet the challenges of the future, foresters will have to use all of the modern tools of management in a thoughtful and integrated manner.

Acknowledgements

I would like to acknowledge the contributions of Kim A. Scoullar to the development of FORCYTE, and to Min Tsze, Patsy Quay, Michael Feller, Philip Comeau, Werner Kurz, Richard Bigley, Wayne Martin, Joy Parkinson, George Krumlik, John Yarie, Ken Lertzman, Maria Ferreira, Linda Christanty, Dan Binkley, Jennifer de Catanzaro, and other graduate students who contributed to the research program that supported the model's development. The financial support of the Canadian Forestry Service, and the encouragement of Jock Carlisle, Lake Chatarpaul, Michael Apps and many others made the development of FORCYTE and the ideas contained in this paper possible. To these and all the many others who have encouraged and contributed to the development of the FORCYTE philosophy and approach, my sincere thanks. John Worrall, Gordon Weetman and David Haley kindly read the manuscript for me and made some useful suggestions.

Literature Cited and Bibliography

Baskerville, G. L. 1985. Forestry research in Canada with particular reference to funding university research. Unpubl. draft mss. Cited with permission.

Baskerville, G. L. 1986. An Audit of Management of the Crown Forests of Ontario. Report to The Hon. V. G. Kerrio, Minister of Natural Resources, Province of Ontario.

Kimmins, J. P. 1985. Future shock in forest yield forecasting: The need for a new approach. Forestry Chronicle 61(6): 503–513.

Kimmins, J. P. 1986. Predicting the consequences of intensive forest harvesting on long term productivity: The need for a hybrid model such as FORCYTE 11. pp. 31–84. *In* Ågren, G. I. (ed.), Predicting Consequences of Intensive Forest Harvesting on Long Term Productivity. Swed. Univ. Agric. Sci. Dept. Ecol. & Environ. Res. Rept. Nr. 26.

Kimmins, J. P. and K. A. Scoullar. 1986. FORCYTE 11 User's Manual. (Unpublished).

Kimmins, J. P., K. A. Scoullar, R. E. Bigley, W. Kurz, P. G. Comeau and L. Chatarpaul. 1986. Yield prediction models: The need for a hybrid ecosystem level approach incorporating canopy function and architecture. pp. 26–48. *In* T. Fujimori and D. Whitehead (eds.), Crown and Canopy Structure in Relation to Productivity. Proc. IUFRO Symposium Workshop. Forestry and For. Prod. Res. Inst., Ibaraki, Japan.

Martin, W. L. 1985. Post clearcutting forest floor nitrogen dynamics and regeneration response in the Coastal Western Hemlock Wet Subzone. Ph.D. thesis, Univ. of British Columbia, Vancouver, B. C. 350 pp.

Rowe, J. S. 1961. The level-of-integration concept and ecology. Ecology 42: 420–427.

Sachs, D. 1983. Management effects on nitrogen nutrition and long term productivity of western hemlock stands: an exercise in simulation with FORCYTE. M.Sc. thesis, Oregon State Univ., Corvallis.

Yarie, J. 1986. FORCYTE Extension of a stand level growth and yield model utilizing nitrogen dynamics to taiga white spruce forests. pp. 190–204. *In* K. van Cleve et al. (eds.), Forest Ecosystems in the Alaska Taiga. Springer Verlag, NY.

Keynote Address:

MODELING THE SUSTAINABILITY OF FOREST PRODUCTION AND YIELD FOR A CHANGING AND UNCERTAIN FUTURE

J.P. Kimmins
University of British Columbia
Vancouver, B.C.

DEDICATION

This paper is dedicated with great respect to the memory of Dr. Peter J. Rennie, who has been an inspiration to those working in long-term site productivity since his pioneering work in the United Kingdom in the early 1950s. His more recent concerns over acid rain and the greenhouse effect provided leadership to forest scientists working on these topics. He will be missed but remembered with respect.

ABSTRACT

The expected growth of the human population to about 11 billion within the next rotation of most northern temperate forest crops will put greatly increased and varied demands on today's forested lands. Development of the timber resources on these lands must be demonstrably sustainable if forest management is to help arrest rather than aggravate the continuing deterioration of the global environment. The experience-based models traditionally used by foresters cannot predict future forest growth and yield accurately for the altered growing conditions that are expected to accompany the population increase. Knowledge-based, process simulation stand growth models are the only way of predicting future forest growth on a particular site in the absence of accurate data on the past growth of forests on that site. Because they have either been too simple or, if sufficiently complex, have had unacceptably large calibration data requirements that have limited their portability, they have been restricted to research and educational applications. An alternative approach combines "historical bioassay" and process-based modeling approaches into "hybrid simulation" stand models that can provide a way to rank the most probable outcomes and the sustainability of alternative stand-level management strategies under anticipated growing conditions. As the world experiences increasing problems of air pollution, soil degradation, and deforestation, there is an urgent need for foresters to use ecosystem-level growth models that are sensitive to human-induced and naturally caused environmental changes.

INTRODUCTION

The single most important factor affecting the future of the world's forests is the continuing growth of the human population, to an anticipated level of about 11 billion (World Bank 1984; Reppetto 1987; Brown et al. 1988). This doubling of the present population is expected to occur within the time necessary for coniferous crops planted on most Canadian clear-cuts in 1989 to reach harvestable condition. Human population growth will lead to a reduction in the area of forest and an increase in demand from the remaining forest for timber products (Council on Environmental Quality 1980; Industrial Working Party 1982; Ford 1983), renewable biomass fuels, chemical feed stocks, clean water, water storage,

transportation and power-transmission corridors, recreational experiences, and wilderness and wildlife values. More forest resources will be demanded from a forest land base that is increasingly restricted to less productive sites with poorer soils (Thorud 1983). Accompanying the population growth, it is expected that air pollution will get a lot worse before it gets better, with attendant problems of acid rain, ozone damage to vegetation, and climate change due to the accumulation in the atmosphere of greenhouse gasses. (Shands and Hoffman 1987; Bolin et al. 1986; Bell 1986; Morrison 1983, 1984; Binkley et al. 1989).

The United Nations reacted to these concerns by appointing the World Commission on Environment and Development under the chairmanship of Norway's Prime Minister, Dr. Gro Harlem Brundtland. A major conclusion of their final report, *Our common future* (World Commission on Environment and Development 1987), was that although the industrialized countries bear a heavy responsibility for the present and past deterioration of the global environment, the greatest long-term threat to the environment comes from poverty in the rapidly growing populations of third world countries. Unless this issue of global poverty can be addressed, the prospects for sustaining or improving the present global environment are not very good. The United Nations Commission concluded that the best hope lies in the wise and sustainable development of renewable resources. Only by doing this can the question of global poverty and unregulated human population growth be resolved. Resources must be developed, but this development must be sustainable, and demonstrably so. The development of resources must also be conducted in a manner that does not threaten other aspects of the global environment.

The demonstration of sustainability requires the use of local, regional, and global resource development planning tools that are capable of predicting the probable long-term consequences of current strategies of resource use. It was suggested at an IUFRO (International Union of Forestry Research Organizations) Working Group meeting in 1987 that stand-level sustainability in temperate forestry involves time scales equal to at least three rotations of temperate tree crops (i.e., 150-300 years). The objectives of this paper are to show that currently used traditional stand-level forest growth and yield models are inappropriate tools for assessing the stand-level sustainability of current forest practices in most areas of the world and to propose an alternative stand-level growth and yield modeling strategy. More complete documentation of arguments presented here have been presented elsewhere (e.g., Kimmins 1985, 1986, 1988; Kimmins and Sollins 1989).

TRADITIONAL GROWTH AND YIELD STAND MODELS IN FORESTRY: experience-based prediction of forest growth and yield

Ever since the method was formalized by German mensurationists in the late 1700s, the standard method of stand-level yield prediction in forestry has been the forward projection of past patterns of forest growth (Assmann 1970). This method, which constitutes a historical bioassay of the growth potential of a site, has the great advantage of not being limited by our still-incomplete knowledge of the ecological and physiological determinants of growth or by research budget and human resource limitations that constrain our attempts to improve this knowledge. Yield tables, and the yield equations or mensurational models based thereon, are implicitly ecosystem-level models, because the historical record of stand development and biomass accumulation integrates the sum of edaphic, climatic, and biotic factors that has affected the trees over the entire rotation.

It is hard to imagine a more believable and practical stand-level growth and yield prediction tool than the traditional mensurational model *if*, and *only if*, one assumption is satisfied: that the future growing conditions are sufficiently similar to those that existed during the rotation on which the model was based (Fig. 1). Within one rotation of the formalization of the yield table method, German mensurationists were reporting that on some sites and under some management regimes, the predictions of mensurational models could be unreliable (Ebermeyer 1976; Rennie 1955, 1957; Assmann 1970). This conclusion was the result of yield declines in north German pine forests in which litter (needles and branches) was raked annually to provide fuel, bedding for cattle, and organic fertilizer. Since that time, yield declines as a result of inappropriate management practices have been reported elsewhere (e.g., second-rotation yield declines in radiata pine in south Australia (Keeves 1966; Squire et al. 1979; Farrell et al. 1981; Squire 1983), and there are many reports of yield increases that have resulted from management-induced improvements in growth conditions. Clearly, the historical bioassay approach is

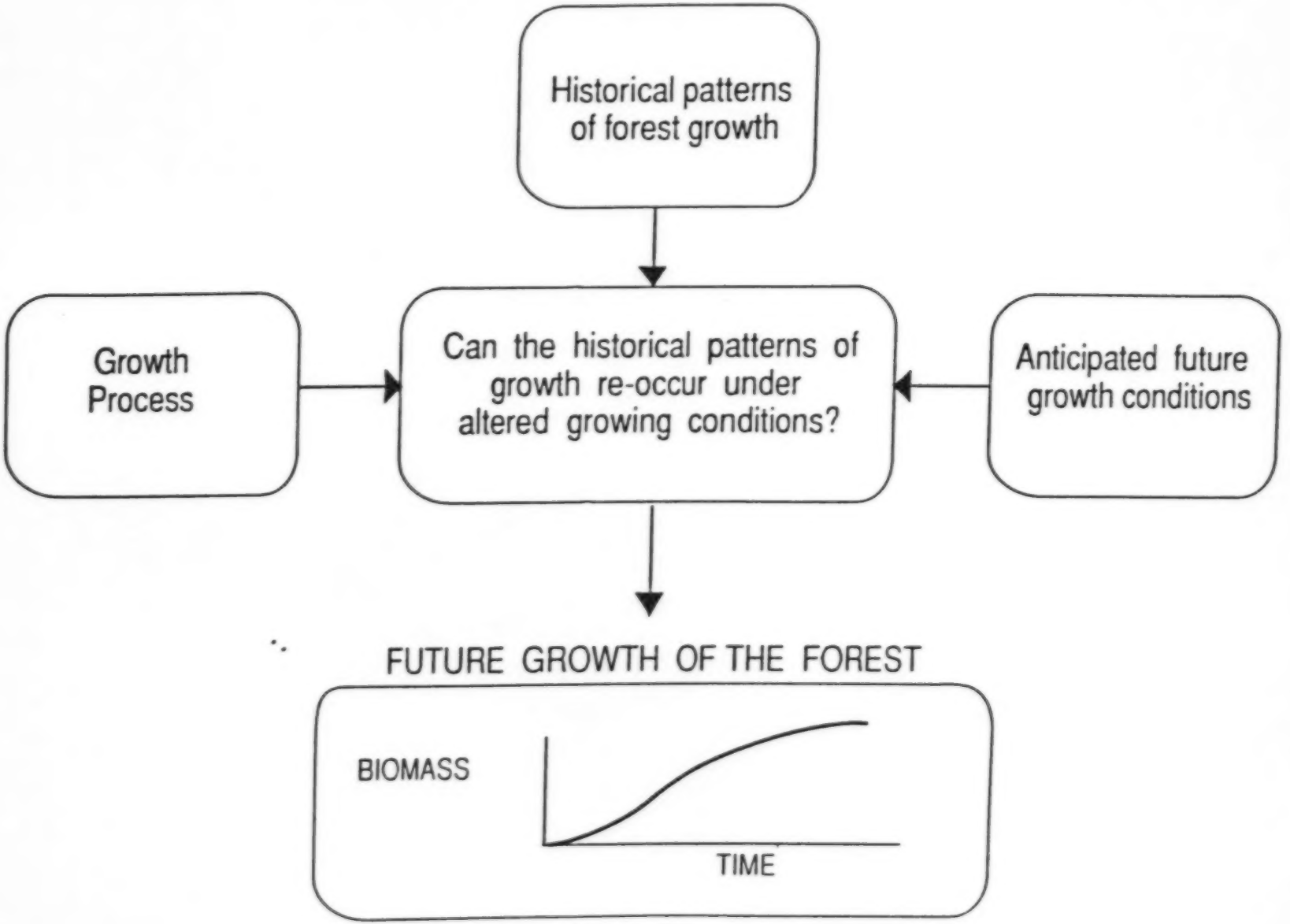

Historical patterns of forest growth
Growth Process
Can the historical patterns of growth re-occur under altered growing conditions?
Anticipated future growth conditions
FUTURE GROWTH OF THE FOREST
BIOMASS
TIME

Figure 4. The hybrid simulation approach to growth and yield forecasting. This method combines the historical bioassay and process-based simulation approaches and takes advantage of the merits of both component approaches.

unsuitable as a basis for yield prediction if the future is significantly different from the past, its undeniable value for unchanging conditions notwithstanding.

The evaluation of traditional approaches to forest growth and yield thus depends on whether or not one believes that future growing conditions will be significantly different from those of the past. Recent predictions about global climate change (e.g., Bolin et al. 1986; Shands and Hoffman 1987) provide persuasive evidence that climates will be altered significantly within the next rotation of northern conifers. Although there is still great uncertainty about these long-term climate predictions at a regional level, there appears to be a broad degree of unanimity among climatologists that the average world temperature will increase between 1.5 and 4.5°C, that the effects will be much greater at higher latitudes (especially in the northern hemisphere) than near the equator, and that winter warming will generally be greater than summer warming. Despite the regional uncertainty, which will probably continue for at least the next decade, these generally agreed-upon global predictions are sufficient on their own to cast grave doubts about the validity of the historical bioassay in many parts of Canada. Cold, northern forests may experience improved growth, while some southern forests may be displaced by grassland. Species requiring winter chilling may be lost in southern or coastal areas.

In addition to climate change, the apparent trend toward more complete utilization of forest biomass (harvest of all above-ground biomass, or of complete trees including stumps and large roots) on shorter rotations using mechanized harvesting poses the risk of significant short and long-term change in soil organic matter and nutrient resources. Loss of soil organic matter has important implications for soil physical structure, soil susceptibility to erosion, soil biology, and soil moisture and nutrient holding capacity. These soil parameters, in conjunction with the total inventory and availability of nutrients, are major determinants of short- and long-term site productivity. Significant reductions in available nutrients due to intensification of management and biomass removals will require fertilization if productivity is to be sustained (Keeney 1980).

Although growth reductions due to nutrient loss have not been as widely documented as growth improvements due to fertilization, there is an increasing body of anecdotal and experimental evidence from research and long-term field trials that documents growth losses (e.g., Lundmark 1977, 1983, 1986; Anderson 1984; Squire 1983). There is abundant evidence of slower tree growth on infertile sites than on fertile sites and evidence that tree growth is limited by nutrient shortages in all the forest regions of Canada (Mahendrappa et al. 1986). Combined with the principles of forest tree nutrition (Ingestad 1987), site nutrient management (e.g., Binkley 1986), biogeochemical theory (e.g., Attiwill and Leeper 1987), and nutrient-based forest management or ecosystem models (Aber and Melillo 1982; Kimmins 1988; Kimmins and Scoullar 1979, 1981, 1983; Pastor and Post 1985; Agren 1986), an unequivocal case can be made that significant nutrient depletion due to intensive biomass harvesting will reduce productivity on many forest sites. It has been suggested that many forest areas have the climatically determined potential to grow at double or even triple the current rates (Axelsson 1983b; Gordon 1982; Gordon et al. 1982) but that the attainment of this potential is normally limited by inadequate nutrition (Axelsson 1983a, 1985).

Soil degradation can cause growth losses at the regional level by reducing the area available for forest growth and by reducing growth on areas that remain forested. It has recently been estimated (Utzig and Walmsley 1988) that management-related soil degradation in British Columbia may be causing as much as $80 million worth of lost forest growth annually and that this loss is increasing by $10 million a year. Although the data on which this estimate is based, and therefore its magnitude, can be questioned, the fact that soil degradation is occurring is unquestionable. It is clear that there is a totally unacceptable level of soil degradation in the province (Lousier and Still 1988), a degradation that renders the predictions of traditional yield models highly suspect.

Climatic and edaphic changes are not the only factors that may alter forest growth and cause future growth and yield to differ from that of the past. The impact of biotic factors may also change. The abundance and species composition of non-crop vegetation may change from one rotation to the next (Nambiar and Zed 1980; Squire 1983), resulting in delays or reductions in crop tree development due to competition, allelopathy, physical interference, or the alteration of the soil nitrogen status. The management-induced removal or increase of early successional nitrogen-fixing species (e.g., alder) can reduce or augment soil nitrogen levels, with important consequences for tree growth (Binkley 1983). If

climate change occurs and causes increased physiological stress in trees, disease and insect problems may increase, with implications for growth and yield. If the climate becomes hotter and drier, fire may be expected to exact a greater toll, reducing regional forest yields both by reducing the area of mature forest and, in some cases, by damaging the soil or its fertility.

Where one wishes to predict the short-term growth response of forest stands to silvicultural treatments, the traditional historical bioassay approach may be acceptable and even optimal. It is unlikely that radical changes in growing conditions will occur in a stand within a 5- or possibly even a 10-year period, for example. Short-term silvicultural responses are relatively uninteresting in Canadian forestry, however. It is the consequences of our management actions and silvicultural investments over the entire rotation that is of major importance (e.g., Lundmark 1977; Kimmins 1986). Considering the changes in forest management that I would anticipate over the next 30-50 years (half of a rotation: see Table 1) and the predicted climatic changes, I do not believe that rotation-length yield predictions based on unmodified historical-bioassay models are credible.

PROCESS-BASED FOREST GROWTH SIMULATION MODELS: knowledge-based prediction of forest growth and yield

The response of forest scientists to the shortcomings of the traditional approach to growth and yield prediction has been to develop models that describe, mechanistically, the processes that determine the quantity of economically recoverable biomass. These models attempt to represent the major ecological and physiological factors that determine the proportion of solar energy thabecomes stored as economically harvestable production (i.e., yield) (Fig. 2). This is usually done by establishing relationships between growth-related parameters and a variety of abiotic and biotic determinants of net biomass accumulation, combining these relationships into a mathematical model, supplying the model

Table 1. Canadian forest management in the future

Possible changes	Possible consequences[1]
Shorter rotations Intermediate harvests (thinnings) More-complete biomass utilization Slash and, in some cases, litter utilization	Depletion of soil organic and nutrients
Greater mechanization	Soil compaction and erosion
Greater control of noncrop vegetation	Loss of species diversity and disruption of successional processes of soil and site recovery
Wider spacing and pruning	Increased competition from noncrop vegetation
Greater use of N-fixing species	Improved site N status and greater diversity of weed species
Greater use of nurse crops, alternating crops, and species mixtures	Altered soil fertility and nutrient cycling
Increased use of fertilization and use of forest as a living filter to recycle urban waste (sewage sludge and processed domestic garbage)	Improved soil fertility and organic matter

[1] Some of the anticipated changes are expected to result in improved growth and yield. Others are expected to have a negative effect.

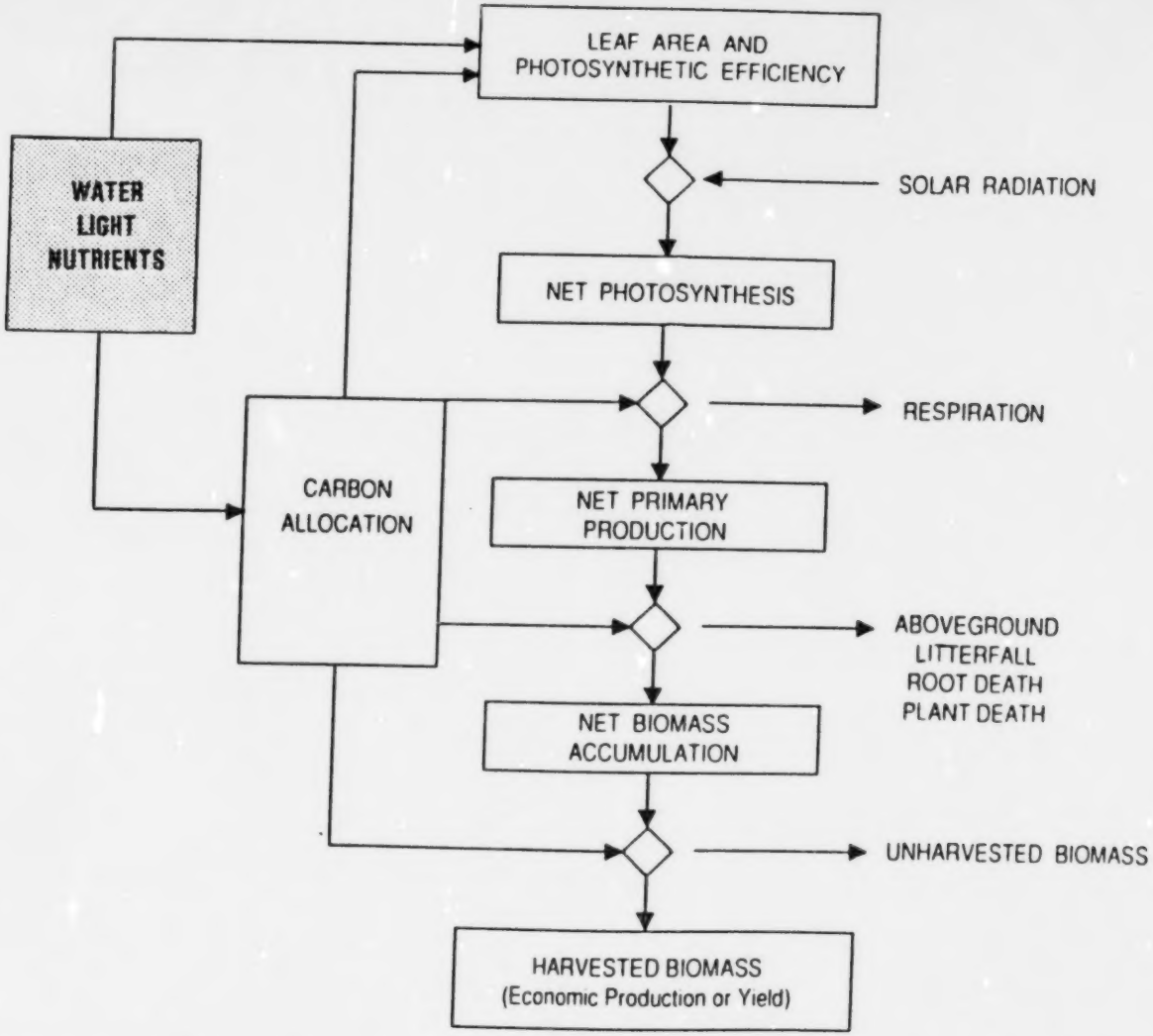


Figure 2. The major determinants of economic production (yield) in a forest ecosystem within a particular climatic regime. Clearly, the availability of site resources (water, light, nutrients) are critically important, both directly and indirectly through their effect on the allocation of net photosynthates.

with input data on the expected future values of these yield determinants, and running the model on a computer (Fig. 3).

Theoretically, this is an ideal approach to the prediction of forest growth and yield because it has the flexibility to deal with altered future growing conditions. In reality, the enormous complexity involved in representing all the myriad processes that determine net biomass accumulation in harvestable biomass components over an entire rotation has limited such models to an educational and research role. In most cases, process-based models of forest growth have lacked one or more major determinants of growth. The reasons for this include inadequate scientific understanding of the processes involved, a lack of knowledge about a known process by the individual developing the model, incomplete data for calibrating the simulation of a known process, the objectives of a particular model (which may have been to model an individual process or subset of the ecosystem rather than the entire rotation length forest growth process), or the lack of access to a computer powerful enough to incorporate simulations of all known processes.

There is a growing number of ecosystem-level models of forest growth (e.g., Mohren 1987; Barclay and Hall 1986) that do include a large proportion of the important growth-determinants, and eventually we may have process-based models that provide a practical alternative to the traditional historical bioassay model. For the foreseeable future, however, the practical application of process-based models will probably be limited by their heavy calibration data demands, which limit their portability. This limitation has led to the development of a third approach to the prediction of future forest growth: hybrid simulation modeling.

HYBRID SIMULATION MODELING OF FOREST GROWTH AND YIELD

The flexibility of the historical bioassay approach and the often overwhelming complexity of the process-based simulation approach has created a need for a new method of stand-level growth and yield prediction. This need can be satisfied by combining the two other approaches into a hybrid simulation model.

The hybrid simulation approach (Fig. 4) assumes that the historical pattern of biomass accumulation is the best estimate we have of future growth of a species or community under unchanging growth conditions (Fig. 1). It then asks the question, "can this historical pattern be repeated if certain growth-determining factors (e.g., nutrient availability, light, competition) change in the future?" In most of the future scenarios one may wish to consider, only a subset of the major growth-determining processes or factors are expected to change. It is a less complex simulation task to modify the historical growth pattern according to a simulation of this subset than to simulate all aspects of ecosystem function that determine net biomass accumulation over rotation.

This first and best-known example of this approach is the JABOWA series of models, developed initially by Botkin et al. (1972) and elaborated by Aber and Melillo (1982), Weinstein et al. (1982), Shugart (1984), Pastor and Post (1985), and Smith and Urban (1988; see also Shugart et al. 1988). Models in the JOBOWA series are gap models (Shugart and West 1980) designed to simulate forest succession over long time periods (many centuries), and this simulation approach has proven to be extremely successful for this purpose. These models have also demonstrated their value for use in predicting the effect of climatic change on forest composition and succession (Solomon and West 1987; Pastor and Post 1988), and there have been efforts, though less extensive than for the successional and climate change applications, to use the models to predict the long-term impacts of forest management on site productivity (Aber et al. 1979, Waldrop et al. 1986).

For multi-tree species, unmanaged forests in which minor vegetation (i.e., the understory) does not play a significant ecological role in determining site productivity, the JABOWA series has much to offer. These gap models use a variety of growth modifiers (the number and type of modifier varies between the different models in the series) to alter the historical pattern of growth of trees regenerating naturally in small gaps created by the death of individual trees. The modifiers are calculated from input data or are simulated dynamically within a model run. There is some concern (Shugart 1984) that the model's simulation of the response of the vegetation to large-scale disturbance (fire, insects, clear-cutting) may deviate increasingly from reality as the simulated area on which vegetation is removed deviates more and more from the small gap (e.g., 1/10 or 1/12 ha) that is assumed in the model structure. Thus, although the patterns of succession in a forest clear-cut in 50-ha patches may differ significantly from

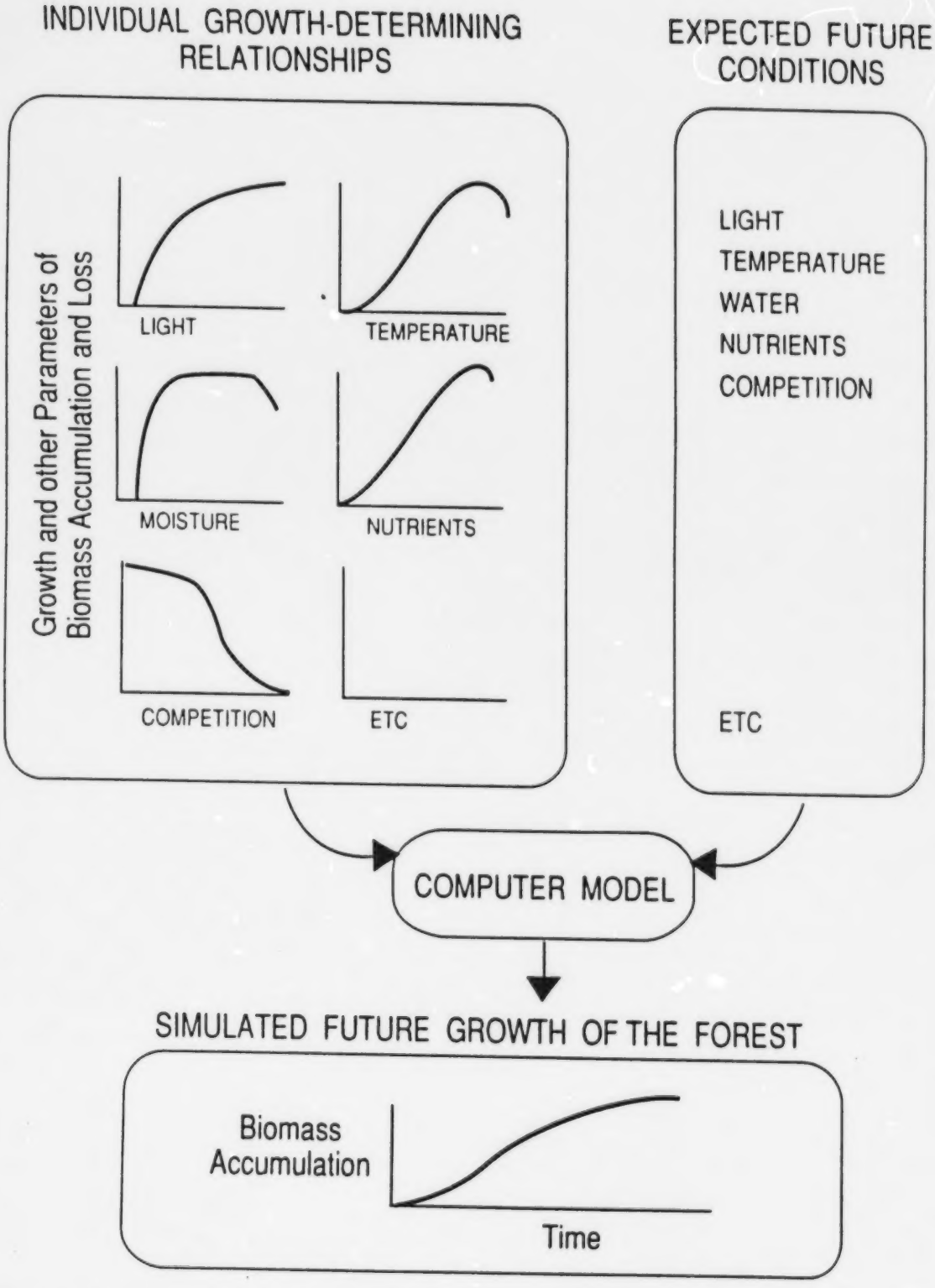


Figure 3. The process-based simulation approach to growth and yield prediction. This is a knowledge-based approach with the flexibility to make accurate predictions for changed future growing conditions.

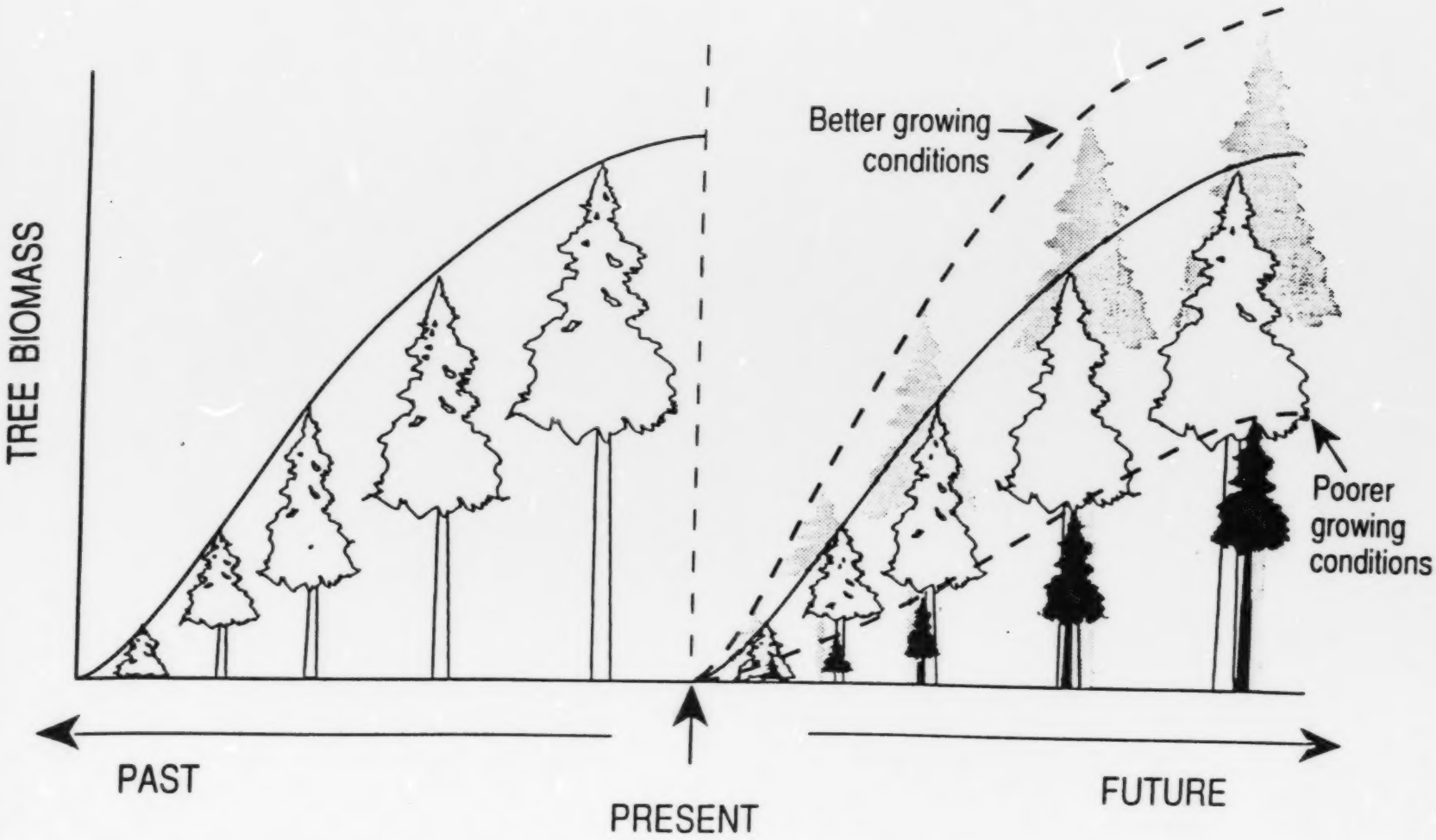


Figure 1. The historical bioassay approach to yield forecasting.

succession in an unmanaged forest, the JABOWA series models will simulate a similar pattern of succession for these two different scales of disturbance. The extent of this possible error has not yet been quantified rigorously to my knowledge. Recent and current modifications of the JABOWA approach, for example, ZELIG[1] (Smith and Urban 1988) should overcome several of these shortcomings.

As the JABOWA series of gap models was being developed by U.S. forest ecologists, the need for a more management-oriented hybrid growth and yield model led to the development of FORCYTE in Canada (Kimmins 1988; Kimmins and Scoullar 1979, 1981, 1983, 1990). The genesis of this development was the ENFOR (ENergy from the FORest) program developed jointly by Forestry Canada and Energy, Mines and Resources Canada. The objective of the model was to examine the economic and energy cost-benefit performance of alternative forest energy plantation or other intensive biomass-for-energy management strategies. In satisfying this objective it became necessary to develop a rather detailed simulation of forest ecosystem function. The result was a hybrid simulation forest ecosystem management modeling framework that has proven to be applicable in a variety of forestry and agroforestry situations around the world.

The FORCYTE models have several capabilities that are not yet available in the JABOWA series. Conversely, the JABOWA-derived models have some abilities that have not yet been added to the latest FORCYTE version (FORCYTE-11). The choice of which type of model to use will therefore depend on the particular objectives of the model user.

The structure and capabilities of the FORCYTE series will not be described here. Details can be found in Kimmins (1986, 1988), Kimmins and Sollins (1989), and Kimmins and Scoullar (1990).

CONCLUSIONS

Although there is debate over the implications of the recommendations of the World Commission on Environment and Development, there is little disagreement over the need to ensure that all present and future resource use and development must be sustainable and demonstrably so. This consensus implies the need for planning tools with which to examine the sustainability of forest management. The traditional forest growth and yield prediction methods used in forestry are only credible in this role if one assumes that future growing conditions (defined by the combination of management practices and environmental conditions) will remain very similar to those of the past. The evidence in favor of no future change in growing conditions is very weak in comparison to that indicating significant change in soils, climate, fire, and biotic conditions. If one accepts this conclusion, one must also accept the need for a new generation of stand-level forest growth and yield prediction tools. The best available alternative that has been developed so far would appear to be the hybrid simulation approach.

[1] Burton, D. Personal communication.

ACKNOWLEDGMENTS

The development of FORCYTE was funded by Forestry Canada under the supervision of Drs. A. Carlisle, L. Chatarpaul, and M.J. Apps. This funding and supervision is gratefully acknowledged, as are the contributions of K.A. Scouller (modeler and programmer), of many graduate students, and of the support staff at the University of British Columbia, all of whom have done so much over the years to assist in the development of my ideas.

REFERENCES

Aber, J.D.; Botkin, D.B.; Melillo, J.M. 1979. Predicting the effects of different harvesting regimes on forest floor dynamics in northern hardwoods. Can. J. For. Res. 9:10-14.

Aber, J.D.; Mellilo J.M. 1982. FORTNITE: A computer model of organic matter and nitrogen dynamics in forest ecosystems. Coll. Agric. Life Sci., Univ. Wisc., Madison, Wisc. Res. Bull. R3130.

Agren, G.I., editor. 1986. Predicting consequences of intensive forest harvesting on long-term productivity. Proc. IEA/BE Proj. CPC-10 Workshop, Jadros, Sweden. Swedish Univ. Agric. Sci., Dep. Ecol. Environ. Res., Uppsala, Sweden. Rep. 26.

Andersson, S.O. 1984. Logging residue is good for the forest. Pages 98-99 in B. Andersson and S. Falk, eds. The Forest Energy Project. Swedish Univ. Agric. Sci., Garpenberg, Sweden.

Assmann, E. 1970. The principles of forest yield study (Translated by S.H. Gradiner). Pergamon Press, New York, N.Y.

Attiwill, P.M.; Leeper, G.W. 1987. Forest soils and nutrient cycles. Melbourne Univ. Press, Melbourne, Australia.

Axelsson, B. 1983a. Methods for maintenance and improvement of forest productivity in northwestern Europe. Pages 305-311 *in* R. Ballard and S.P. Gessel, eds. Forest site and continuous productivity. Proc. IUFRO Symp. USDA For. Serv., Pac. Northwest For. Range. Exp. Stn., Portland, Oreg. Gen. Tech. Rep. PNW-163.

Axelsson, B. 1983b. Ultimate forest productivity: What is possible? Pages 61-60 *in* R. Ballard and S.P. Gessel, eds. Forest site and continuous productivity. Proc. IUFRO Symp. USDA For. Serv., Pac. Northwest For. Range. Exp. Stn., Portland, Oreg. Gen. Tech. Rep. PNW-163.

Axelsson, B. 1985. Increasing forest productivity and value by manipulating nutrient availability. Pages 5-38 *in* R. Ballard, P. Farnum, G.A. Ritchie, and J.K. Winjum, eds. Forest potentials: productivity and value. Weyerhaeuser Science Symposium 4. Weyerhaeuser Company, Tacoma, Wash.

Barclay, J.H.; Hall, T.H. 1986. SHAWN: A model of Douglas-fir ecosystem response to nitrogen fertilization and thinning: a preliminary approach. Can. For. Serv., Pac. For. Cent., Victoria, B.C. Inf. Rep. BC-X-280.

Bell, J.N.B. 1986. Effects of acid deposition on crops and forests. Experimentia 42:363-371.

Binkley, D. 1983. Ecosystem production in Douglas-fir plantations: interaction of red alder and site fertility. For. Ecol. Manage. 5:215-227.

Binkley, D. 1986. Forest nutrition management. Wiley-Interscience. J. Wiley and Sons, New York, N.Y.

Binkley, D.; Driscoll, C.T.; Allen, H.L.; Schoeneberger, P.; McAvoy, D. 1989. Acidic deposition and forest soils. Springer-Verlag, New York, N.Y.

Bolin, D.B.; Doos, B.R.; Jager, J.; Warrick, R.A. 1986. The greenhouse effect, climate change, and ecosystems. SCOPE Report 29. J. Wiley and Sons, New York, N.Y.

Botkin, D.B.; Janak, J.F.; Wallis, J.R. 1972. Some ecological consequences of a computer model of forest growth. J. Ecol. 60:849-872.

Brown, L.R.; Chandler, W.U.; Durning, A.; Flavin, C.; Heise, L.; Jacobson, J.; Pastel, S.; Shea, C.P.; Starke, L. 1988. State of the world 1988. A Worldwatch Institute report on progress towards a sustainable society. Worldwatch Inst., Norton & Co., New York, N.Y.

Council on Environmental Quality. 1980. The Global 2000 report to the President: Entering the twenty-first century. U.S. Gov. Print. Off., Washington, D.C.

Ebermeyer, E. 1876. Die gesammte Lehre der Waldstreu mit Rucksicht auf die chemische Statik des Waldbaues. J. Springer-Verlag, Berlin.

Farrell, P.W.; Flinn, D.W.; Squire, R.O.; Craig, F.G. 1981. On the maintenance of productivity of radiata pine monocultures on sandy soils in southeast Australia. Pages 117-128 *in* XVII IUFRO World Congr. Div. 1 Proc. Jpn. IUFRO Congr. Comm., For. For. Prod. Res. Inst., Ibaraki, Japan.

Ford, E.D. 1983. What do we need to know about forest productivity and how can we measure it? Pages 2-12 *in* R. Ballard and S.P. Gessel, eds. Forest site and continuous productivity. Proc. IUFRO Symp. USDA For. Serv., Pac. Northwest For. Range Exp. Stn., Portland, Oreg. Gen. Tech. Rep. PNW-163.

Gordon, J. 1982. Productivity of Washington's forests: improving forest productivity. Pages 1-5 *in* Proc. Symp. For. Prod. Wash. State. Univ. Wash., Coll. For. Resour., Seattle, Wash.

Gordon, J.; Farnum, P.; Timmis, R. 1982. Theoretical maximum phytomass yields as guides for yield improvement. Pages 19-34 *in* Physiology and genetics of intensive culture. Proc. 7th N. Am. For. Biol. Workshop. Univ. Kentucky, Dep. For., Lexington, Kentucky.

Industrial Working Party. 1982. World forest products demand and supply—1990 and 2000. FAO For. Devel. Paper.

Ingestad, T. 1987. New concepts on soil fertility and plant nutrition as illustrated by research on forest trees and stands. Geoderma 40:237-252.

Keeney, D.R. 1980. Prediction of soil N availability in forest ecosystems: a literature review. For. Sci. 26:159-171.

Keeves, A. 1966. Some evidence of loss of productivity with successive rotations of Pinus radiata in the southeast of South Australia. Austr. For. 30:51-63.

Kimmins, J.P. 1985. Future shock in forest yield forecasting: the need for a new approach. For. Chron. 61:503-513.

Kimmins, J.P. 1986. FORCYTE in forestry: the need for a systems approach in forest education, yield prediction and management: Pages 1-25 *in*: The E.B. Eddy Distinguished Lecture Series. Univ. Toronto, Fac. For., Toronto, Ont.

Kimmins, J.P. 1988. Community organization: methods of study and prediction of the productivity and yield of forest ecosystems. Can. J. Bot. 66:2654-2672.

Kimmins, J.P.; Scoullar, K.A. 1979. FORCYTE: A computer simulation approach to evaluating the effect of whole tree harvesting on the nutrient budgets of northwest forests. Pages 266-273 *in* S.P. Gessel et al., eds. For. Fert. Conf. Proc. Contrib. 40. Univ. Wash., Inst. For. Res., Seattle, Wash.

Kimmins, J.P.; Scoullar, K.A. 1981. FORCYTE: a computer simulation approach to evaluating the effect of whole tree harvesting on nutrient budgets and future forest productivity. Mitt. Forstl. Bunderversuchsanst, Wien. 140:189-205.

Kimmins, J.P.; Scoullar, K.A. 1990. FORCYTE-11 user's manual. For. Can., North. For. Cent., Edmonton, Alberta. (In press.)

Kimmins, J.P.; Sollins, P. 1989. Modelling long-term forest productivity. *In* D.A. Perry et al., eds. Maintaining the long-term productivity of Pacific Northwest forest ecosystems. Timber Press, Portland, Oreg. (In press.)

Lousier, J.D.; Still, G.W. 1988. Degradation of forest land: forest soils at risk. Proc. 10th B.C. Soil Sci. Workshop. B.C. Minist. For., Land Manage. Rep. 56.

Lundmark, J.E. 1977. [The soil as part of the forest ecosystem.] Marken som del av det skogliga ekosystemet. Pages 109-122 *in* [The care of the soil. Properties and utilization of forest soils.] Markvård. Skogsmarkens egenskaper och utnyttjande. Sveriges Skogsvårdsforbunds Tidskrift Vol. 75.

Lundmark, J.E. 1983. [Growth effects of whole-tree harvesting on different site types – forecasts based on basics of biology.] Produktionsekologiska effekter på olika ståndorts typer vid heltradutnyttjande. – prognos baserad på biologisk grundsyn. Swedish Univ. Agric. Sci. Skogsfakta. Suppl. 1.

Lundmark, J.E. 1986. [Short-term and long-term effects on site productivity by soil treatments in forestry.] Skogen som Natur och Resurs. Forskarnas slutsatser om skoglig markvard. Swedish Univ. Agric. Sci. Skogsfakta Konferens 9.

Mahendrappa, M.K.; Foster, N.W.; Weetman, G.F.; Drause, H.H. 1986. Nutrient cycling and availability in forest soils. Can. J. Soil Sci. 66:547-572.

Mohren, G.M.J. 1987. Simulation of forest growth, applied to Douglas-fir stands in the Netherlands. Ph.D. thesis. Landbouwuniversiteit, Wageningen, Netherlands.

Morrison, I.K. 1983. Acid rain, forests, and forestry. Pages 209-219 *in* E.L. Stone, ed. Forest soils and treatment impacts. Proc. 6th N. Am. For. Soils Conf. Univ. Tenn., Knoxville, Tenn.

Morrison, I.K. 1984. Acid rain. A review of the literature on acid deposition effects in forest ecosystems. For. Abstr. 45:483-506.

Nambiar, E.K.S.; Zed, P.G. 1980. Influence of weeds on the water potential, nutrient content, and growth of young radiata pine. Austr. For. Res. 10:279-288.

Pastor, J.; Post, W.M. 1985. Development of a linked forest productivity soil process model. Oak Ridge Natl. Lab., Oak Ridge, Tenn. Environ. Sci. Div. Publ. 2455. ORN/TM-9519.

Pastor, J.; Post, W.M. 1988. Response of northern forests to Co_2-induced climate change. Nature 334:55-58.

Rennie, P.J. 1955. Uptake of nutrients by mature forest growth. Plant Soil 7:49-95.

Rennie, P.J. 1957. The uptake of nutrients by timber forest and its importance to timber production in Britain. Q. J. For. 51:101-115.

Repetto, R. 1987. Population, resources, environment: an uncertain future. Popul. Bull. 42(2).

Shands, W.E.; Hoffman, J.S., editors. 1987. The greenhouse effect, climate change, and U.S. forests. The Conservation Foundation, Washington, D.C.

Shugart, H.H. 1984. A theory of forest dynamics. The ecological implications of forest succession models. Springer-Verlag, New York, N.Y.

Shugart, H.H.; West, D.C. 1980. Forest succession models. BioScience 30(5):308-313.

Shugart, H.H.; Michaels, P.J.; Smith, T.M.; Weinstein, D.A.; Rosteiter, E.B. 1988. Simulation models of forest succession. Pages 125-151 *in* T. Rosswall, R.G. Woodmarsee, and P.G. Risser, eds. Scales and global change. J. Wiley and Sons, New York, N.Y.

Smith, T.M.; Urban, D.L. 1988. Scale and resolution of forest structural pattern. Vegetatio 74:143-150.

Solomon, A.M.; West, D.C. 1987. Simulating forest ecosystem responses to expected climate change: applications to decision-making in the forest industry. Pages 189-217 *in* W.E. Shands and C.J. Hoffman, eds. The greenhouse effect, climate change, and U.S. forests. The Conservation Foundation, Washington, D.C.

Squire, R.O. 1983. Review of second rotation silviculture of *Pinus radiata* plantations in southern Australia: establishment practices and expectations. Pages 130-137 *in* R. Ballard and S.P. Gessel, eds. Forest site and continuous productivity. Proc. IUFRO Symp. USDA For. Serv., Pac. Northwest For. Range Exp. Stn., Portland, Oreg. Gen. Tech. Rep. PNW-163.

Squire, R.O.; Flinn, D.W.; Farrell, P.W. 1979. Productivity of first and second rotation stands of radiata pine on sandy soils. I. Site factors affecting early growth. Austr. For. 42(4):226-235.

Thorud, D.B. 1983. Opening remarks. Page 1 *in* R. Ballard and S.P. Gessel eds. Forest site and continuous productivity. Proc. IUFRO Symp. USDA For. Serv., Pac. Northwest For. Range Exp. Stn., Portland, Oreg. Gen. Tech. Rep. PNW-163.

Utzig, G.F.; Walmsley, M.E. 1988. Evaluation of soil degradation as a factor affecting forest productivity in British Columbia: a problem analysis. Phase 1. Can. For. Serv., Pac. For. Cent., Victoria, B.C. Canada-British Columbia Forest Resource Development Agreement Rep. 025.

Waldrop, T.A.; Buckner, E.R.; Shugart, H.H.; McGee, C.E. 1986. FORCAT: a single tree model of stand development following clearcutting on the Cumberland Plateau. For. Sci. 32:297-317.

Weinstein, D.A.; Shugart, H.H.; West, D.C. 1982. The long-term nutrient retention properties of forest ecosystems: a simulation investigation. Oak Ridge Natl. Lab., Oak Ridge, Tenn. ORNL/TM-8472.

World Bank. 1984. World development report. Oxford Univ. Press, Oxford, England.

World Commission on Environment and Development. 1987. Our common future. Oxford Univ. Press, Oxford, England.

Unpublished report:

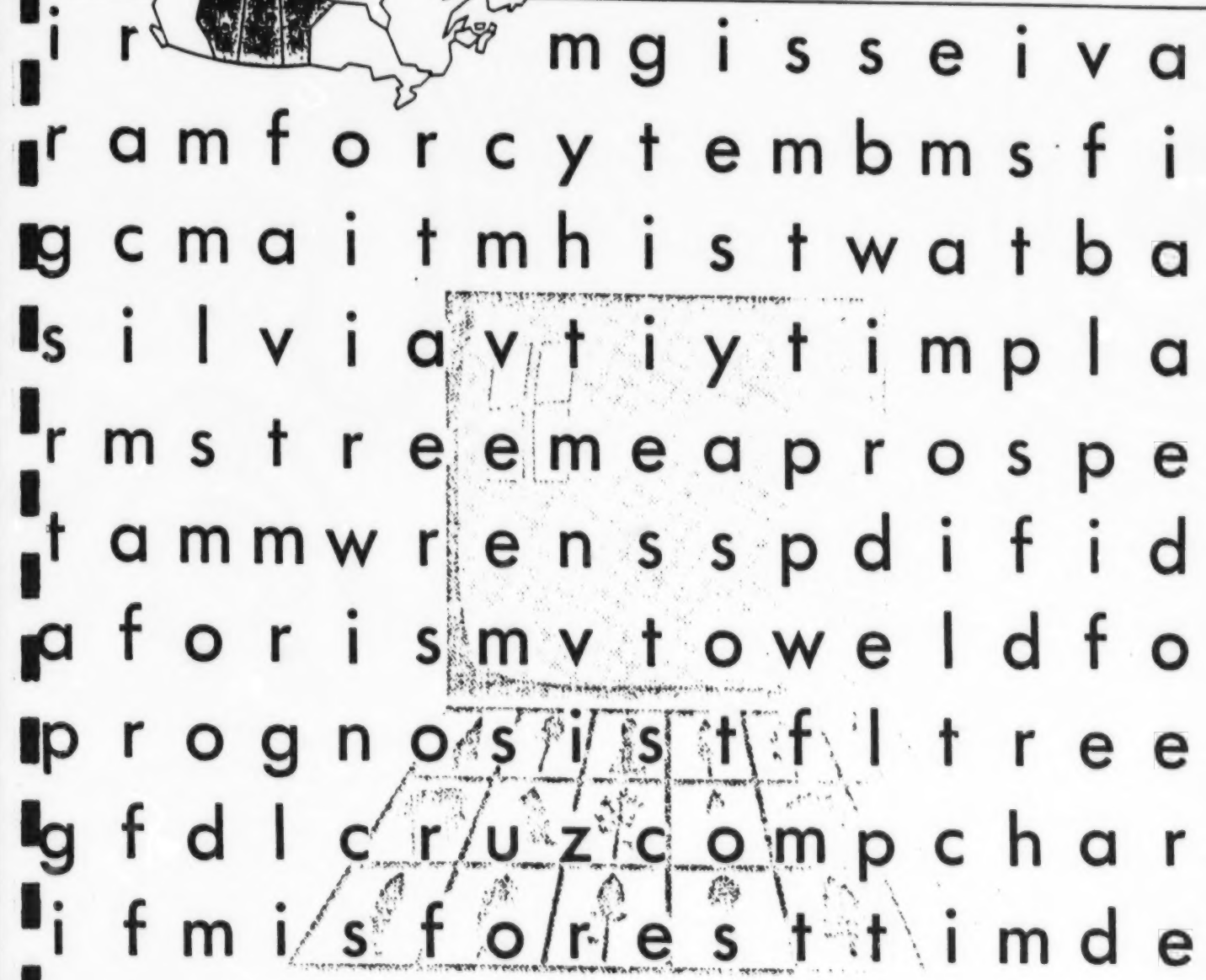
Kimmins, J.P.; Scoullar, K.A. 1983. FORCYTE-10. A user's manual for the tenth version of the FORest nutrient Cycling and Yield Trend Evaluator. Second approximation. Prepared for the Canadian Forestry Service, Ottawa, Ont.

Forestry Canada Forêts Canada

Forest Modeling Symposium

B.J. Boughton and J.K. Samoil, editors

Information Report NOR-X-308
Northwest Region


i r m g i s s e i v a
r a m f o r c y t e m b m s f i
g c m a i t m h i s t w a t b a
s i l v i a v t i y t i m p l a
r m s t r e e m e a p r o s p e
t a m m w r e n s s p d i f i d
a f o r i s m v t o w e l d f o
p r o g n o s i s t f l t r e e
g f d l c r u z c o m p c h a r
i f m i s f o r e s t t i m d e
s a s s m o d e l i n g p r i s
f e p a s y m p o s i u m c r a

PAPER ON OLD-GROWTH FORESTS
FROM THE 1990 MCGRAW-HILL YEARBOOK
OF SCIENCE AND TECHNOLOGY

of these bacteria to provide nutrition for their hosts may have allowed the loss of particulate feeding abilities, for example, filter-feeding capacities, by the animals.

One attribute of all of the sulfur-oxidizing symbiotic bacteria is that, unlike the better-studied free-living thiobacillus species, the symbiotic species store large deposits of elemental sulfur in the periplasmic space. This elemental sulfur can apparently serve as an energy reserve when environmental sources of sulfide are low. Elemental sulfur can form over 10% of the dry weight of the tissue containing the symbionts. These deposits of elemental sulfur disappear rapidly when the animals are placed in sulfide-free seawater.

For background information *SEE BACTERIAL PHYSIOLOGY AND METABOLISM; CYTOCHROME; POGONOPHORA; RESPIRATORY PIGMENTS (INVERTEBRATE)* in the McGraw-Hill Encyclopedia of Science & Technology.

Alissa J. Arp, George N. Somero; Russell D. Vetter

Bibliography. A. E. Anderson, J. J. Childress, and J. A. Favuzzi, Net uptake of CO_2 driven by sulphide and thiosulphate oxidation in the bacterial symbiont-containing clam *Solemya reidi*, *J. Exp. Biol.*, 133: 1–31, 1987; A. J. Arp, J. J. Childress, and R. D. Vetter, The sulphide-binding protein in the blood of the vestimentiferan tube worm *Riftia pachyptila* is the extracellular hemoglobin, *J. Exp. Biol.*, 128:139–158, 1987; J. J. Childress, H. Felbeck, and G. N. Somero, Symbiosis in the deep sea, *Sci. Amer.*, 255: 115–120, 1987.

Forest and forestry

The pressure to feed, house, and otherwise supply the growing human population over the past half century has resulted in an unprecedented rate of global deforestation, and an increasing extent and intensity of exploitation or management of the remaining forest. As a result, the area of land supporting the mature or old-growth forest that existed before humans became a dominant ecological factor is declining rapidly. There are many reasons why it would be prudent to reserve significant areas of such unmanaged forests, and there is growing public concern that reservations should be established soon, before the opportunity has been lost.

Characteristics of old-growth forest. Establishment of an adequate series of reserves requires a clear definition of old-growth forest, so that appropriate areas can be identified. Old-growth forests are those forests that have developed for a sufficient period of time in the absence of catastrophic disturbance (for example, catastrophic fire, insect epidemics, or wind damage; clearcut harvesting) to satisfy some particular definition of the key characteristics of this kind of forest. The definition will be different for different types of forest. Old-growth coniferous boreal forest in northern Canada or the Soviet Union is different from old-growth coniferous temperate rainforest in the Pacific Northwest of the United States, as is old-growth temperate rainforest in Tasmania (giant eucalyptus forest; see illus.) from the Pacific Northwest old-growth, and old-growth beech forest in Europe from that of the eastern United States deciduous hardwood forest. Some characteristics of old-growth may be common to most of these definitions, but others will be specific to a certain type of forest. These characteristics will probably include one or more of the following: age and size of dominant trees, species composition, structure, and successional stage of the forest, and accumulation of dead organic matter.

Forest of mature stringybark, *Eucalyptus obliqua*, approximately 230 ft (70 m) tall and 220 years old, in Tasmania with an understory of sassafras, *Atherosperma moschatum*, a temperate rainforest species. (*Leigh Edwards, Tasmanian Forestry Commission*)

Age of dominant trees. The age of the dominant trees, or the time since the previous catastrophic disturbance, is a primary characteristic of old-growth forest. Many of the characteristics that make old-growth forests different from younger forests take a long time to develop, and so stand or tree age may be the best single indicator of the old-growth condition. Douglas-fir forests on productive sites in the United States Pacific Northwest may develop some old-growth characteristics in 150 to 250 years; however, full development of Douglas-fir as an old-growth tree may require 500 years or more on good sites, and much longer on sites where the trees grow slowly. For tree species (such as pines) that do not live as long as Douglas-fir (which can sometimes live for more than 1000 years), the old-growth condition will develop much sooner. Old-growth balsam fir stands in eastern Canada may be about 150 years old, or younger.

Size of dominant trees. Many of the values associated with old-growth forests are simply the result of the presence of many very large trees. Such trees have recreational (esthetic and spiritual) values for humans and habitat values for old-growth-dependent species

of wildlife. For long-lived Pacific Northwest species such as Douglas-fir, western redcedar, or Sitka spruce, it may take 500 to 1000 years for the trees to achieve their maximum diameters, although height growth may become very slow or even stop after only a couple of hundred years. Alaska yellow cedar can continue to increase in diameter for as long as 1500 years. In the forests of giant *Eucalyptus* species which grow in the humid parts of Australia, maximum tree size may be achieved in less than 350 years on some sites.

The enormous size of these temperate rainforest species obviously satisfies the old-growth definition. However, many tree species in old-growth tropical, temperate deciduous, and boreal forests achieve much more modest dimensions, even in old age. It is just as important that areas of these more diminutive old-growth forests are reserved.

Species composition. Many plant and animal species are found in both old-growth and younger forests, but there are some species that have a preference for, or are largely restricted to, some types of old-growth. For example, in the Douglas-fir forests of the Pacific Northwest, the northern spotted owl, Vaux's swift, the fisher, the western red-backed vole, and the Olympic salamander have a preference for, or are dependent on, old-growth forest. Plant species diversity may be lower in some types of coniferous old-growth than in somewhat younger forests on the same site, but it is thought that total species diversity may be higher in these old-growth forests than in the younger forests that precede them. Old-growth tropical forests generally have a higher species diversity than secondary tropical forest. Thus, old-growth forests sometimes have a different combination of species than younger forests in the same area, and where this is true old-growth can be characterized by a unique combination of species. This uniqueness may be mainly in the animal species, or in the plant, animal, and microbial species.

Successional stage. Old-growth forest is sometimes a climax or self-replacing biotic community (for example, western hemlock and western redcedar forest in the Pacific Northwest). However, some of the largest and most magnificent old-growth forests in the world (for example, the giant eucalypt forests of Australia) require periodic disturbance if the large trees are to be perpetuated. Without disturbance these forest giants are replaced by relatively diminutive temperate rainforest species. Douglas-fir and Sitka spruce in the humid coastal Pacific Northwest also require disturbance, but because they can be so long-lived they may survive in the forest for a very long time without disturbance once they are established. In parts of the world where forest fire has been a frequent and dominant ecological factor, vast areas may be covered by pine, eucalypt, or other fire-maintained pioneer tree species. Old-growth in such areas is usually the oldest stands of these pioneer species.

Accumulation of dead organic matter. Old-growth forests in the cool humid coastal areas of the Pacific Northwest are often characterized by an abundance of large decomposing logs on the ground, a thick forest floor, and many large dead trees (snags). In drier or in warmer areas where the decomposition of organic matter is rapid (because of fire in hot dry climates and rapid decomposition in hot humid climates), old-growth may lack such large accumulations of dead organic matter. Thus, the ground in old-growth tropical forest usually has a very different appearance from the ground in Pacific Northwest coastal old-growth forest. If a previous Pacific Northwest forest was killed by a wildfire which left a lot of large dead trees standing and did not consume the organic matter on the ground, these two attributes of old-growth can be found in relatively young forests.

Forest structure. The trees in young forests that have regenerated after fire, windblow, or logging are often relatively uniform in size and age. Such forests tend to have a uniform and closed canopy and a monotonous structure. In contrast, many types of old-growth are characterized by a very variable structure. Climax old-growth forests generally have trees of all sizes and ages in intimate mixture, or may consist of a mosaic of small patches of forest of different size and age, all the trees within each patch being quite similar. These small patches may have originated in gaps in the overstory canopy created by the death of individual large old trees. This structural diversity in the overstory leads to increased spatial diversity in the understory. The combined overstory and understory plant diversity often leads to increased animal diversity.

The meaning of the term old-growth will obviously vary in different types of forest, and it would be inappropriate to use the same definition everywhere. Separate definitions are needed for each type of forest in order to ensure that representative areas of all the world's great diversity of old-growth forests are conserved.

Old-growth forest reservations. Because old-growth forest varies so much in its characteristics in different parts of the world, and because of the lack of accurate up-to-date information about most of the world's forests, it is difficult to say just how much old-growth forest remains. However, as the pressure to exploit and manage the world's forests increases, the remaining area that satisfies some definition of old-growth is declining rapidly, and it becomes more and more important that adequate areas of old-growth are reserved in the near future. Such areas are needed for a variety of purposes: as ecological reserves, for recreational and public educational activities, for research and professional education, as wildlife habitat, and for the maintenance of species and genetic diversity.

Ecological reserves. Examples are needed of unmanaged ecosystems as ecological reserves or environmental benchmark areas against which can be measured the impacts of forest management, and the effects of anthropogenically induced changes in atmospheric chemistry (for example, acid rain), and the accompanying effects on climate (the greenhouse effect) and radiation quality (increases in ultraviolet radiation due to changes in ozone in the upper atmosphere).

Recreational and public educational activities. Old-growth forest is required for recreational and public educational activities. Many individuals find viewing of old-growth forest very attractive, and the knowledge that the ecosystem has been relatively undisturbed by humans, or at least by industrialization, for a long period of time gives such forests emotional and spiritual values that are very different from those of younger, managed forests. The presence of very large or very old trees is important in this respect.

Research and professional education. Areas of old-growth forest are needed for research and professional education. More needs to be understood about the ecosystem conditions to which late successional species have become adapted if the methods of managing such species for timber or other forest values are going to be successful.

Habitat. Old-growth forest may be required as habitat for certain wildlife species which depend on large old trees or other features of the old-growth forest ecosystem. Unless wildlife species that are characteristic of old-growth forests can adapt to the ecological conditions present in younger, managed forests, or unless the ecological conditions these species require can be reproduced by appropriate forest and wildlife management techniques in the managed forest, such species may be lost from an area or may even become extinct.

Maintenance of biological diversity. Maintenance of high regional biological diversity may require the reservation of areas of old-growth. Although scattered areas of clearcut harvesting in an extensive area of unbroken old-growth forest will often increase the species diversity of the region, diversity may decline again if the entire area is converted to young managed forest. The extent of this decline will depend in part on how rapidly the area is converted to young forest (that is, how many different age classes of forest are created). Maximum regional diversity may result from a mosaic of young managed forest of various ages combined with ecologically significant areas of old-growth reserve.

Size and location. It is much easier to agree that old-growth reserves are required than to define their optimum size and location. The size required to sustain specific old-growth values will depend on what the values are, the type of forest, the climate, and the land use of the area around the reserve.

If old-growth forest reserves are too small, they may be very susceptible to damage or alteration by wind. If their purpose is to provide wildlife habitat, they must be large enough to satisfy the territorial and other spatial requirements of the particular species. If the population of an old-growth–dependent wildlife species in a reserve is too small, it may lack sufficient genetic diversity or breeding population size to be able to survive. Similarly, if the reserves are too small, wildlife pressure on the plants may be so great that the floristic composition and structure of the forest may change over time and some plant species may be lost. This would greatly reduce the value of such areas as ecological reserves. Unfortunately, for most species, knowledge of the critical minimum area of old-growth forest is inadequate. It is the opinion of most ecologists who are studying old-growth that the size of such reserves is generally too small to ensure that the old-growth condition will be conserved.

There is a tendency to want to reserve areas of old-growth on very productive sites (because of the magnificence of the large trees on such sites) and to ignore old-growth forest on less productive sites which lack big trees. Although this approach may satisfy many of the recreational and esthetic needs for old-growth reserves, it is not a suitable basis on which to establish an adequate system of ecological reserves, which should be representative of all the old-growth ecosystems in a particular climatic zone. The esthetic, emotional, and spiritual values of big-tree forests do not necessarily satisfy the other reasons for old-growth reserves. However, the pressure from forest harvesting is normally greatest for forests with big trees, and this is the most threatened type of old-growth. It is appropriate, therefore, that conservation efforts should focus initially on this type of forest.

It is clear that the size and location of old-growth reserves should be decided on a site-specific and objective-specific basis.

Old-growth forest values. Ecosystems are constantly changing. Natural or human-assisted invasions of "new" insects, diseases, and plant competitors; changes in the frequency and intensity of fire; changes in climate, animal populations, soil fertility, and ecosystem processes, together with the natural sequence of community change that normally follows ecosystem disturbance (ecological succession), all contribute to alterations in the structure, function, and species composition of forest ecosystems as time passes. Reserving a particular area of old-growth does not guarantee that future generations can enjoy the particular set of values that led to the initial reservation of that area.

The best way of ensuring that future generations will be able to enjoy old-growth forest, and that they will have an ecological benchmark against which the successes and failures of environmental and resource management can be judged, is to recognize that forest ecosystems change, to understand how they change naturally, and to identify how that change is affected by human activities. On the basis of this understanding for particular forests in particular climates and landscapes, strategies can be devised to provide a continuous or renewable supply of old-growth forest values.

Any program of old-growth conservation will undoubtedly include reserves that will remain unmanaged in perpetuity, ecosystem change being observed and recorded but not managed. In some cases this may involve an entire major valley system (greater than 50,000 acres or 20,000 hectares), the size and location of which will be determined by the objectives of the reserve. In many cases, however, reservation objectives may be satisfied better by the distribution of the same area between a series of pocket wilderness reserves varying in area from several hundred to a few

thousand hectares (1 hectare = 2.5 acres), the size depending on the particular type of forest and the particular old-growth values that are to be conserved. At least one such reserve should be established in each major valley system and should include the range of sites within that system. In many cases, this can be done best by having the reserve go from valley bottom to the height of land or by reserving an entire small valley watershed.

In those cases in which perpetuation of the desired old-growth values requires periodic disturbance (for example, the giant eucalypt old-growth forest in southern Australia), management and harvest of forests on a long rotation (as much as several hundred years) may be necessary. Such long-rotation management areas could conveniently be clustered around a permanent old-growth reserve. Alternatively, the concept of temporary old-growth reserves could be adopted. This could involve a two-tier system of reserves: a set of old-growth reserves paired with a set of younger reserves (which include mature trees). If, with the passage of time, natural ecosystem change reduces the major values for which an old-growth reserve was established, it would be harvested and replaced by the younger reserve. This would be left unmanaged until such time that it also lost its major values, when it would, in turn, be replaced by a younger stand which had been put into secondary reserve status at the time the initial old-growth reserve was harvested. This strategy would maintain areas of old-growth in perpetuity but not in the same location. The time scale for this rotation of old-growth areas would depend on the time scale of natural change, and no change in area might be necessary for one or two centuries.

Conclusions. As humans continue to alter the surface of the Earth, it becomes increasingly important to create ecological reserves and environmental benchmark areas and to reserve areas of old-growth wildlife habitat and wilderness. Sometimes these reserves can be located in existing park areas, but in most parts of the world there is a pressing need to create new reserves outside parks. Success in conserving old-growth values requires a clear definition of what old-growth is. Because old-growth forests vary so much in their characteristics in different parts of the world, a flexible, site-specific approach to defining this type of forest is needed. All ecosystems change with time, and conservation strategies should recognize this propensity to change. If necessary, conservation must include management strategies to ensure that future generations are able to enjoy the full diversity of old-growth forests that can be found on the planet Earth.

For background information SEE ECOLOGICAL COMMUNITIES; ECOLOGICAL SUCCESSION; ECOSYSTEM; FOREST ECOLOGY; FOREST ECOSYSTEM; FOREST FIRE CONTROL; FOREST MANAGEMENT; FOREST RESOURCES; REFORESTATION; TREE DISEASES in the McGraw-Hill Encyclopedia of Science & Technology.

J. P. Kimmins

Bibliography. J. F. Franklin et al., Ecological characteristics of old-growth Douglas-fir forests, USDA For. Serv., PNW For. Range Exp. Sta. Gen. Tech. Rep. PNW-118, 1981; L. D. Harris, *The Fragmented Forest: Island Biogeography Theory and the Preservation of Biotic Diversity*, 1984; J. P. Kimmins, *Forest Ecology*, 1987; T. A. Spies and J. F. Franklin, Old-growth and forest dynamics in the Douglas-fir region of western Oregon and Washington, *Nat. Areas J.*, 8(3):190–201, 1988.

Fuse (electricity)

Conventional high-voltage fuses used on electric distribution lines rely on a separately tripped protective device to deal with low overload currents. Recently developed types of so-called full-range fuses cover the whole range of current overloads in a single fuse element. This article discusses the drawbacks of conventional high-voltage fuses, the reasons for their unsatisfactory performance at low overcurrents, and the design and application of the new full-range fuses.

High-voltage fuses. High-voltage current-limiting electrical fuses are widely used for the protection of distribution transformer systems. Advantages of this type of fuse are its ability to interrupt high levels of short-circuit current and its energy-limiting action which ensures against serious damage to transformers and associated lines and equipment in the event of major faults.

Unfortunately, unlike most low-voltage fuses, these high-voltage fuses have a well-defined lower limit to the range of fault currents which can be safely interrupted. Typically a 15-kV, 50-A fuse may have a minimum melting current of about 75 A (1.5 times the rated current I_n), yet the minimum safe interrupting current could be as high as 150 A (3 times I_n). This would mean that in the band of currents between 1.5 I_n and 3 I_n the fuse could be called upon to clear a system fault, yet would not be able to do so safely. A disruptive failure could occur with consequent risk of severe damage to surrounding equipment. In many service conditions this unsafe zone is made wider (Fig. 1) because of the derating effect of fuse enclosures and the presence of neighboring fuses of a three-phase set. In the relevant fuse specifications these fuses are termed backup fuses since, for those applications where low overcurrent faults are thought likely to occur, some other protective device has to be used in series with the fuse to take care of low fault currents. Backup fuses are therefore often used either in series with expulsion fuses or in association with a fuse switch tripped out by the fuse striker pin. Used in this way, backup fuses are perfectly safe at all fault currents, but the size, cost, and complexity of the installation are adversely affected. For such applications the need has long been recognized for an improved type of high-voltage current-limiting fuse which would have no lower safe interrupting current limit and which could therefore be used in any service application as the sole protective device.

A design for such a fuse was first described in 1965.